دانشگاه سمنان

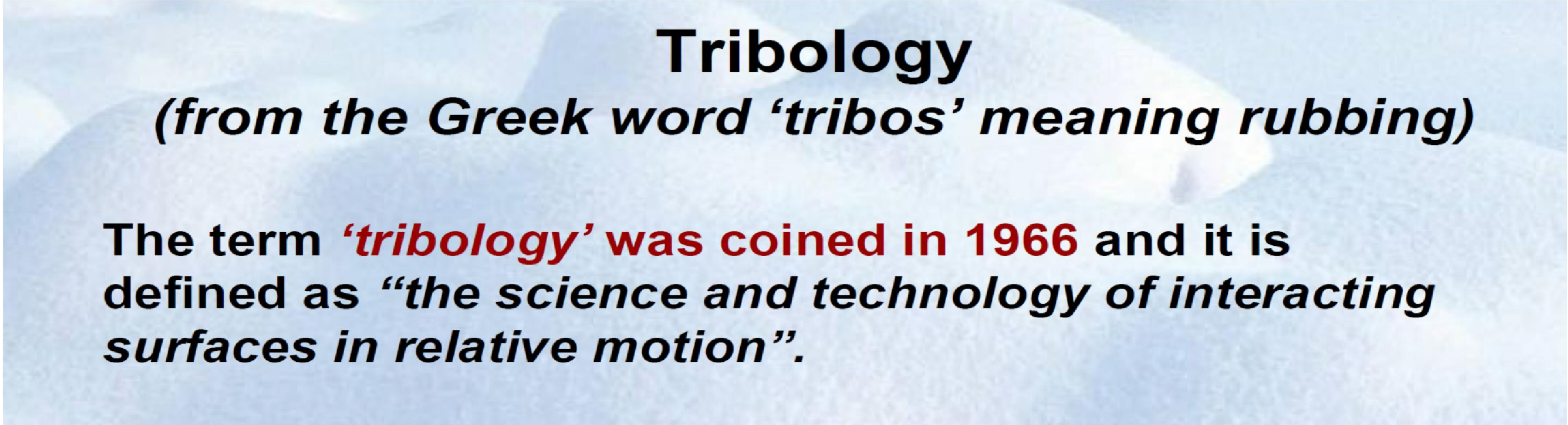
Tribology

Collected by: M. Azadi

References

- Friction, wear, lubrication, A textbook in tribology, K.C Ludema, 1996 CRC Press.
- The Tribology Handbook, 1989, published by Halstead Press (Ed. M.J. Neale).
- The ASM (Vol. 18) Handbook of Tribology, 1994 (Ed. P.J. Blau)

Introduction



Tribology

(from the Greek word 'tribos' meaning rubbing)

The term *'tribology'* was coined in 1966 and it is defined as *"the science and technology of interacting surfaces in relative motion"*.

Science: Basic mechanisms

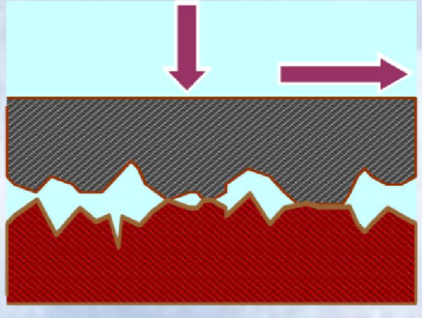
Technology: Design, manufacture, maintenance

It encompasses the study of:

Friction

Wear

Lubrication



Tribology

Friction is defined as the resistance to motion experienced whenever one solid body moves over another.

Friction

Resistance to relative motion

Wear is defined as surface damage or removal of material from one or both solid surfaces during moving contact.

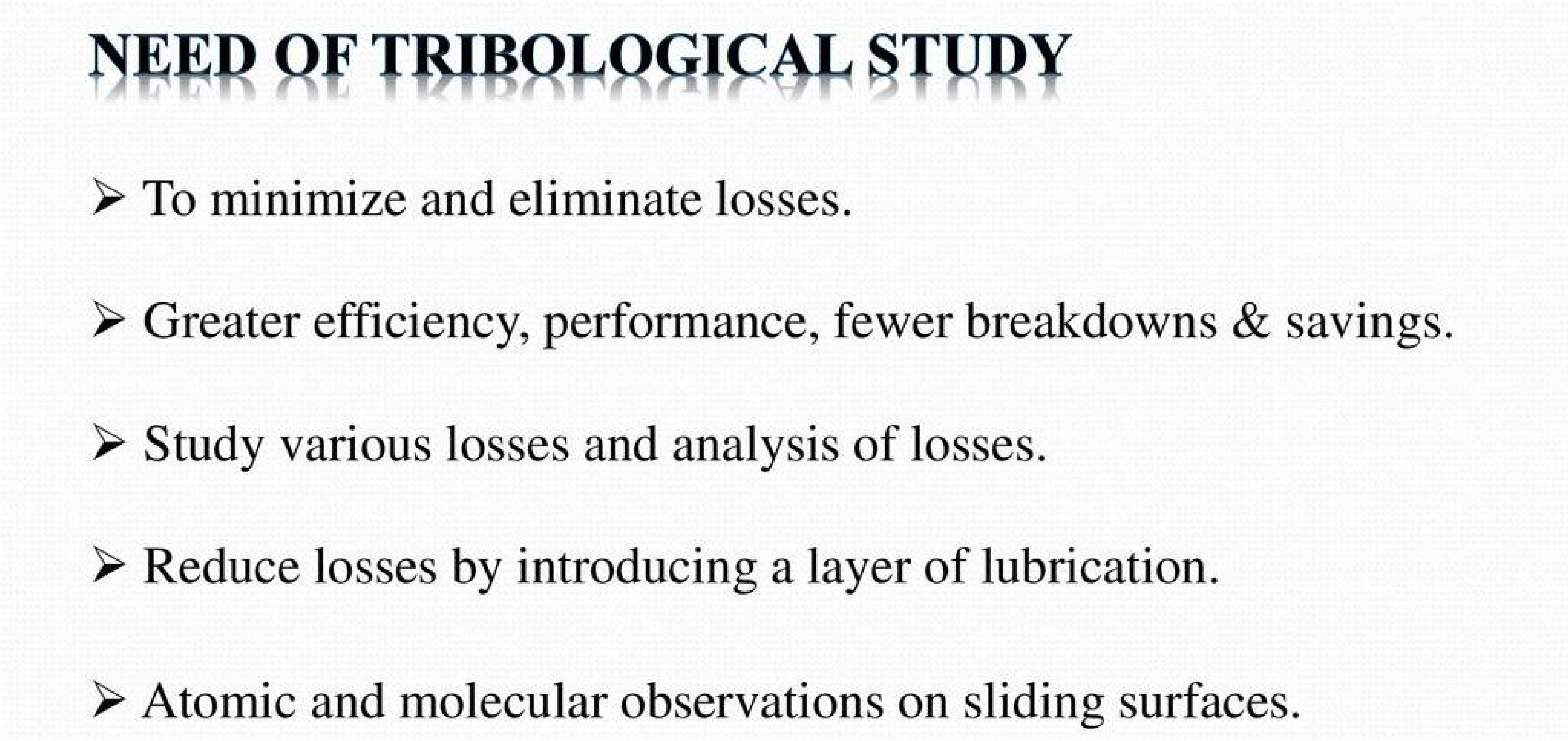
Wear

Gradual removal, damaging or displacement of material.

One of the most effective means of controlling friction and wear is by proper lubrication, which provides smooth running and satisfactory life for machine elements. Lubricants can be solid or gaseous.

Lubrication

Control of friction and wear by introducing a friction-reducing film between moving surfaces in contact.



NEED OF TRIBOLOGICAL STUDY

- To minimize and eliminate losses.
- Greater efficiency, performance, fewer breakdowns & savings.
- Study various losses and analysis of losses.
- Reduce losses by introducing a layer of lubrication.
- Atomic and molecular observations on sliding surfaces.

Probably more failures are caused by tribological problems than fracture, fatigue, plastic deformation.

Tribological knowledge helps to improve service life, safety, and reliability of interacting machine components; and yields substantial economic benefits.

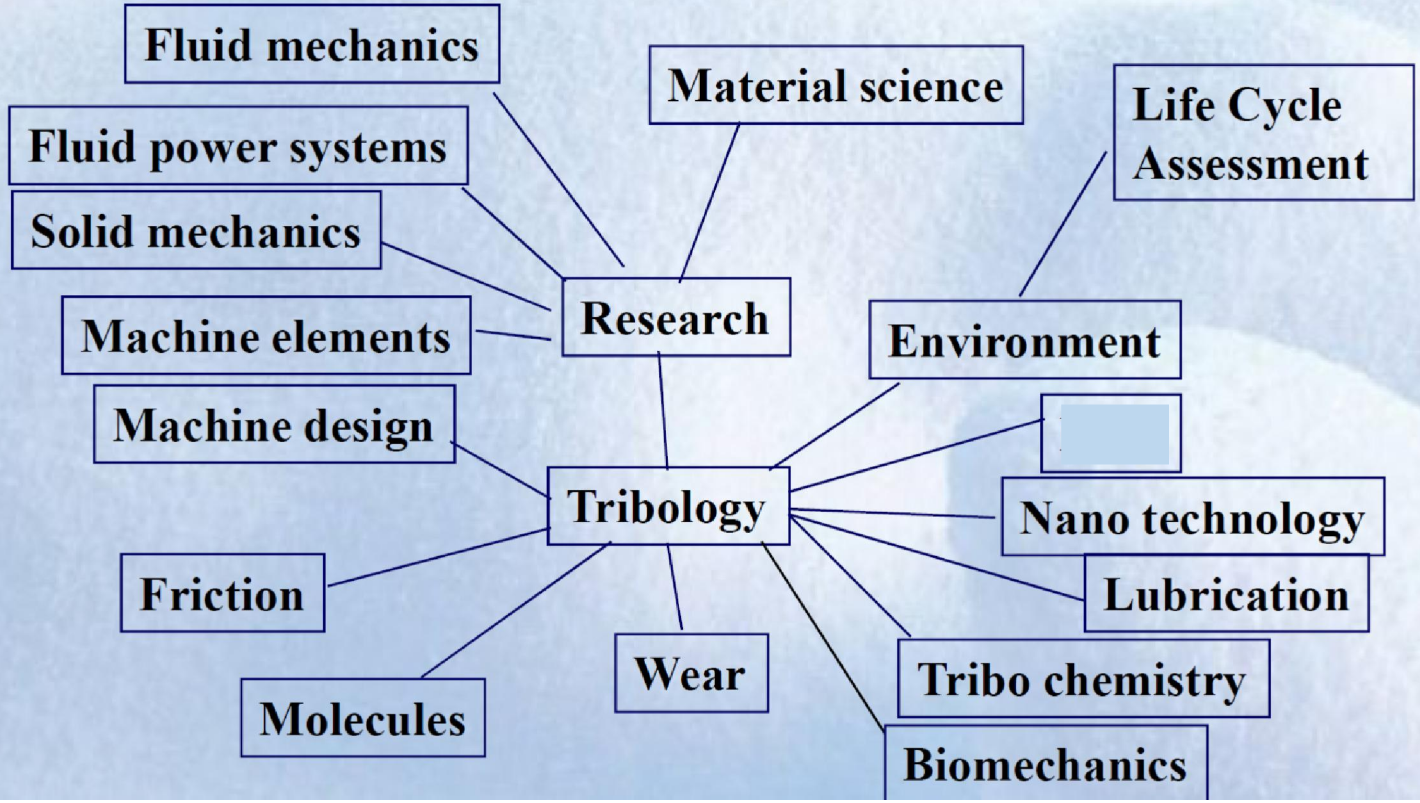
Most tribological phenomena are inherently *complicated and interconnected*, making it necessary to understand the concepts of tribology in detail.

Integration of knowledge from multi-disciplines (solid mechanics, fluid mechanics, material science, chemistry etc) is essential and therefore a separate subject is required.

SOURCES	AMOUNT Million £ (POUNDS)
Reduced Maintenance & Replacement	230
Fewer Breakdowns(Increased Reliability)	110
Longer Machine Life	100
Reduced Frictional Dissipation	25
Savings in Investment	15
Savings in Lubricants	5
Savings in Manpower	5

SAVINGS RELSULTING FROM PROPER UNDERSTANDING AND APPLICATION OF TRIBOLOGY

Tribology is a Multi-Disciplinary Subject



Fluid mechanics

Material science

Life Cycle Assessment

Fluid power systems

Solid mechanics

Research

Environment

Machine elements

Machine design

Tribology

Nano technology

Friction

Lubrication

Wear

Tribo chemistry

Molecules

Biomechanics

Examples

Most mechanical components have one or more moving parts. This means that something is moving relative to something else, so there is tribology happening.

In some components, such as bearings and gears, the goal is to **minimize** the resistance to sliding or rolling so that as little energy as possible is lost to friction.

In other components, such as brakes and clutches, we want **maximum** sliding resistance in order to limit the relative motions.

- BEARINGS –
  Minimal friction & Minimal wear
- BRAKES –
  Maximum friction & Minimal wear
- MACHINING –
  Minimal friction & Maximum wear

Tribology is Everywere- Few Examples

- Tyre-road (high friction required)
- Bearings (low friction and wear required)
- Screw joints (low friction in threading, no wear in contact)
- Ski-snow (low friction for gliding but high in the grip zone)
- Shoe-floor (medium friction for easy walking and dancing)
- Brake-disc (controlled, stable friction, not too low or too high)
- Cam-follower (no wear, low friction)
- Piston ring-cylinder (no wear, low friction)
- Chalk-board (controlled wear process)
- Pen-paper (controlled wear process)
- Artificial joints

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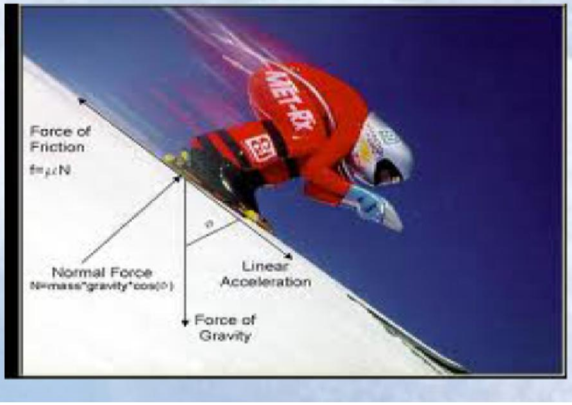

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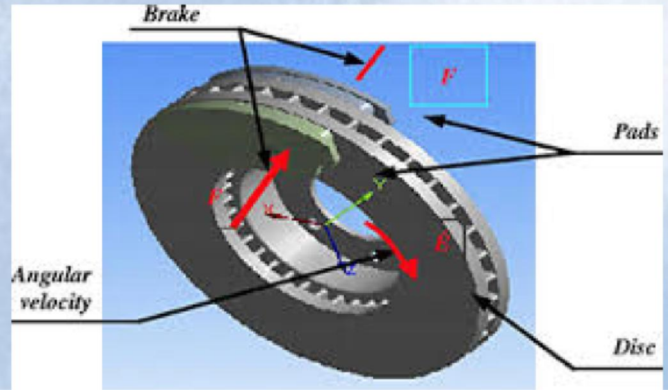

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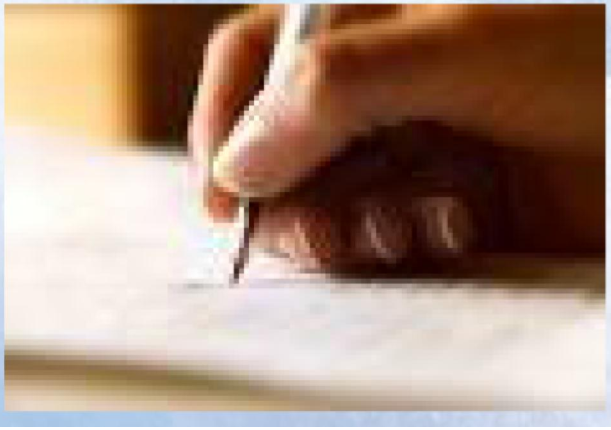


Tribology is Everywere- Few Examples

- Artificial joints

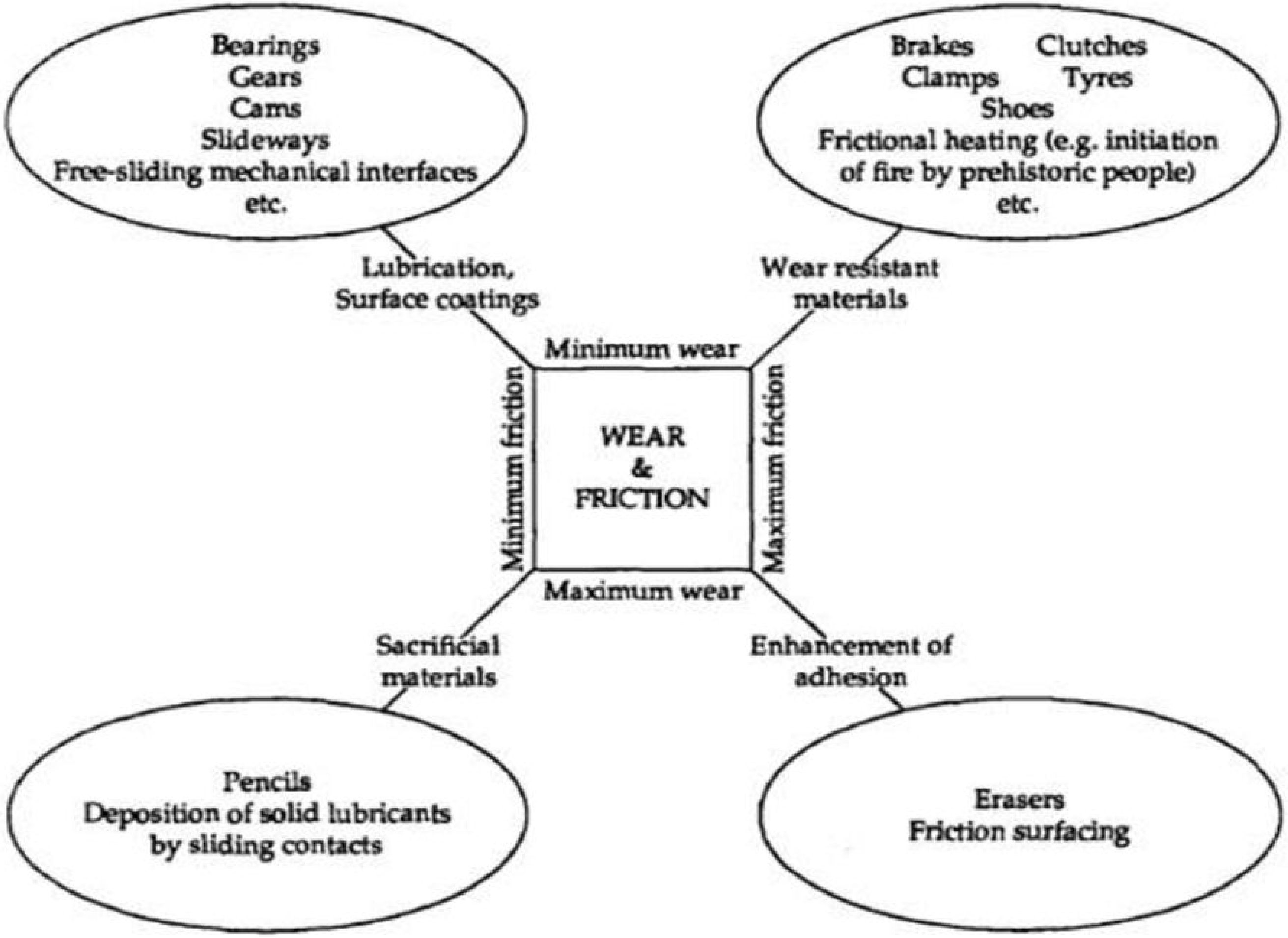


Figure Practical objectives of tribology.

Tribological Examples

- Left hand side is photograph of centrally grooved engine *journal bearing.*
- It appears that bearing is worn out due to foreign particles.

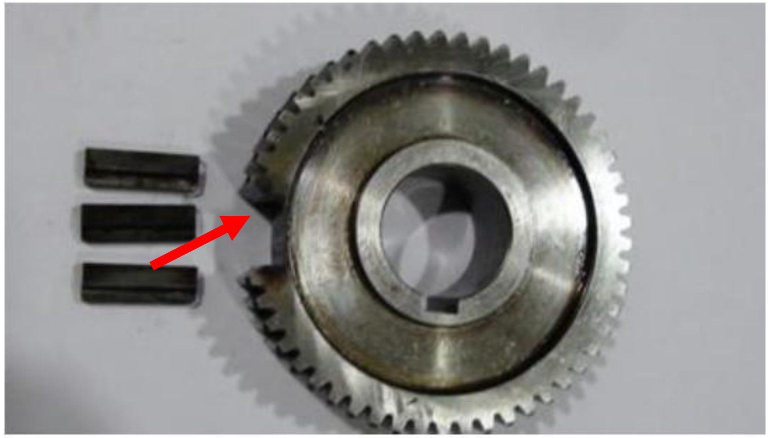
- Right hand side is a photograph of an *aluminum bearing* subjected to heavy load,
- Which causes shaft surface to run over bearing inner surface.

Tribological Examples

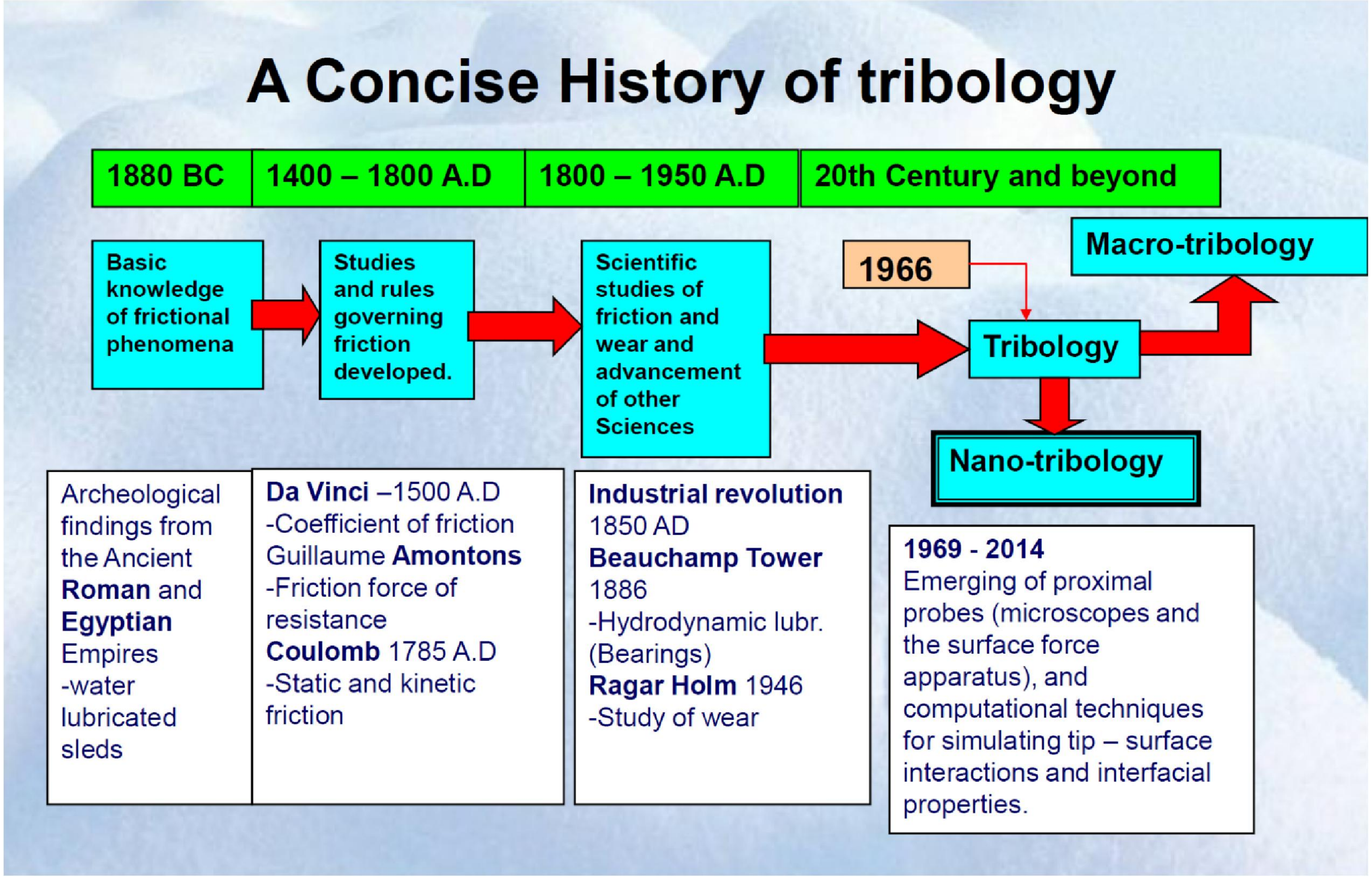
- Deep cracks which breaks outer ring in number of pieces. Such failure occurs due to faulty manufacturing and wrong assembly of *roller bearing*.
- Tribological relations help estimating increase in contact stresses due to misalignment of shaft and improper mounting of bearing surfaces.
- Hence an approximate reduction in service life can be estimated.

Tribological Examples

- A pit on the surface of *gear tooth* is shown in Fig. The pit generally occurs due to excessive contact stress.
- Understanding the effect of contact stress helps in developing an equation for estimation of perspective gear life.



History



A Concise History of tribology

1880 BC	1400 – 1800 A.D	1800 – 1950 A.D	20th Century and beyond

Basic knowledge of frictional phenomena

Studies and rules governing friction developed.

Scientific studies of friction and wear and advancement of other Sciences

1966

Tribology

Macro-tribology

Nano-tribology

Archeological findings from the Ancient **Roman** and **Egyptian** Empires
-water lubricated sleds

Da Vinci –1500 A.D
-Coefficient of friction
Guillaume **Amontons**
-Friction force of resistance
Coulomb 1785 A.D
-Static and kinetic friction

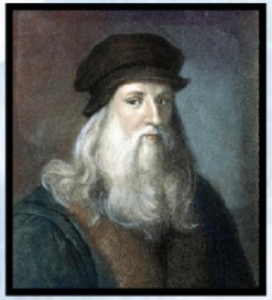
Industrial revolution
1850 AD
Beauchamp Tower
1886
-Hydrodynamic lubr. (Bearings)
Ragar Holm 1946
-Study of wear

1969 - 2014
Emerging of proximal probes (microscopes and the surface force apparatus), and computational techniques for simulating tip – surface interactions and interfacial properties.

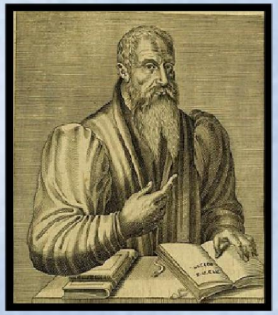
In ancient times, on the order of about 500,000 B.C., early humans learned that by rubbing sticks together with great force they could create fire.

Around 3500 B.C. we learned that rolling motion required less effort than sliding, and the wheel was invented.

1495-1950: Laws of friction are developed



- In 1495 **Leonardo** formulated the two basic laws of friction: Friction is independent of contact area, and friction is proportional to load. For years, he never got credit for his work, as he did not formally publish his observations.



- Some 200 years later, in 1699, **Guillaume Amontons** (1663-1705) rediscovered these two basic laws. He reasoned that friction was primarily the result of work done to lift one surface over the roughness of the other, resulting in deformation and wear of the surfaces.

- **Sir Isaac Newton** (1642-1727), in studying and creating the basic laws of motion, added that moving friction was not dependent on speed or velocity, thus formul-ating the third law of friction. All these observations were made in the macro scale.

- In 1950, **Phillip Bowden** and **David Tabor** gave a physical explanation for the observed laws of friction. They determined that the true area of contact, which is formed by the asperities on the surface of a material, is a very small percentage of the apparent area. As the normal force increases, more asperities come into contact and the average area of each asperity contact grows.

- As our ability to analyze surface contacts at the monomolecular level has developed, we are learning that the “macro” laws don’t necessarily hold and that the processes of interaction are quite complex.

- “*Amontons Laws of Friction are the first quantitative description of a tribological process. Attempts (theories, mechanisms, models) to explain these laws have been central to the development of tribology.*” —**Bill Needelman**, Filtration Science Solutions.

1883-1905: Principles of hydrodynamic lubrication are elaborated

•In 1883, the elucidation of hydro-dynamic lubrication began in England, with testing done by **Beauchamp Tower**. He used a specially constructed test rig for journal bearings, simulating the conditions found in railway axle boxes.

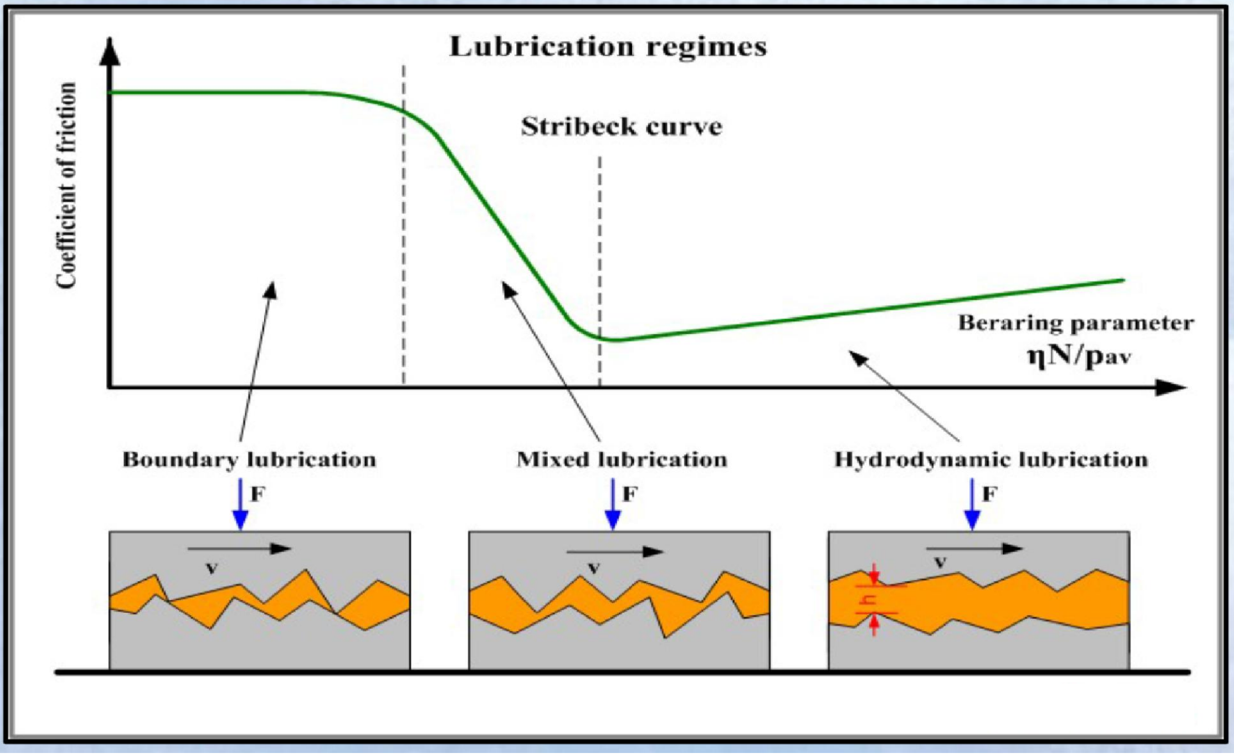
•In the final phase of his research, Tower decided to drill an oil feed hole in the bearing. The oil was found to rise upwards in the feed hole and leak over the top of the bearing cap. He then installed a pressure gauge and found it to be inadequate for measuring the high pressure levels. This result proved the existence of a fluid film that could carry significant loads.

- In 1886 **Osborne Reynolds** published a differential equation describing this pressure buildup of the oil in the narrow converging gap between journal bearing surfaces. This equation, a variation of the Navier-Stokes equations resulting in a second-order differential equation, was so complex that many years passed before it was solved for journal bearings.

- In 1902 **Richard Stribeck**, published the Stribeck curve, a plot of friction as it relates to viscosity, speed and load.

- After the work of Tower and Reynolds, **Arnold Sommerfeld** refined the work into a formal theory of hydrodynamic lubrication in about 1905.

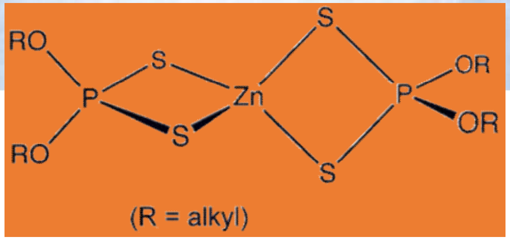
- A surface have tiny asperities that will contact if two plates are placed together. If one of the plates were to slide over the other, then friction would increase, the asperities would break and the surfaces would wear. In hydrodynamic lubrication, a fluid film separates the surfaces, prevents wear and reduces friction.



•In 1912 Dr. Albert Kingsbury invented the **hydrodynamic thrust bearing**.

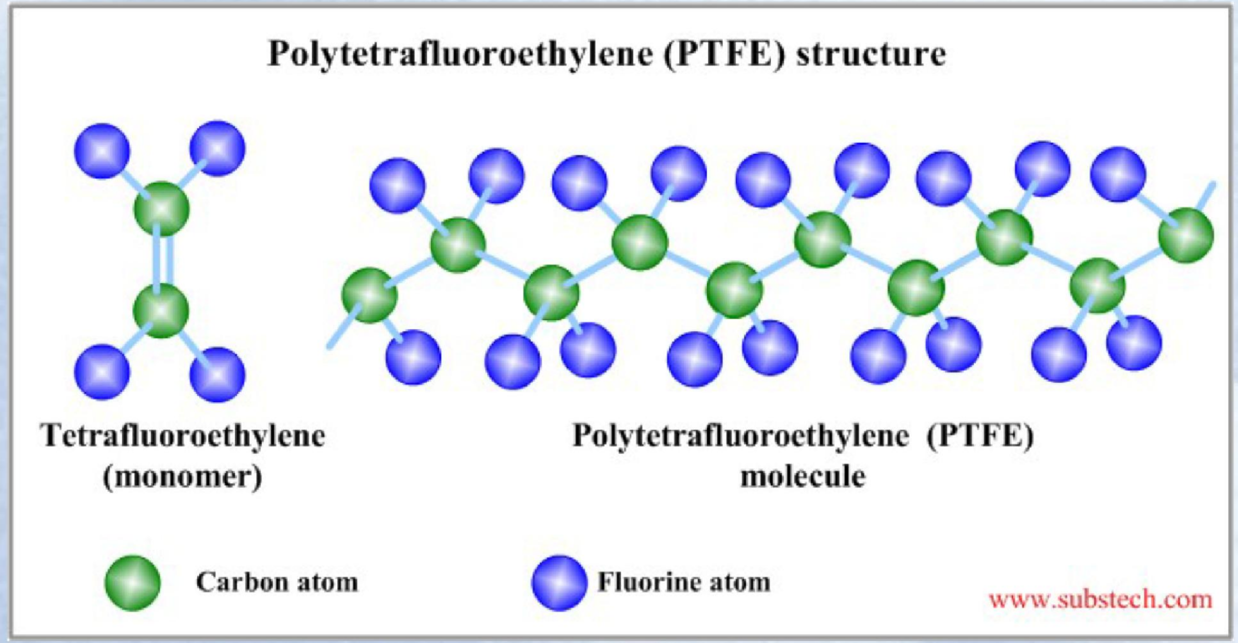
•In 1922 understanding of **Boundary lubrication refined** by W.B. Hardy and I. Doubleday.

•1930s to 1940s The first **zinc dialkyldithiophosphates (ZDDPs)** began to be developed as anticorrosion agents and oxidation inhibitors. The antiwear activity of these molecules was recognized only later, in the 950s, at which point they became an integral part of many oil chemistries. To this day ZDDPs remain the backbone of antiwear additive technology.



(R = alkyl)

- **PTFE**, the most famous of the self-lubricating coating materials, was discovered fortuitously during a project looking at tetrafluoroethylene as a refrigerant.



- In 1942 **Lithium grease** invented & rapidly became widely used multi-purpose grease

- In 1950 **Synthetic oils** introduced for usage in aviation.

- In 1950s **Fire Resistant Hydraulic Fluids** developed.

- In 1962 **Aluminium Complex grease** invented for high temperature applications.

- In 1960s **Multi-grade motor oils** introduced.

- In 1960s **Synthetic oils** used for motor oils.

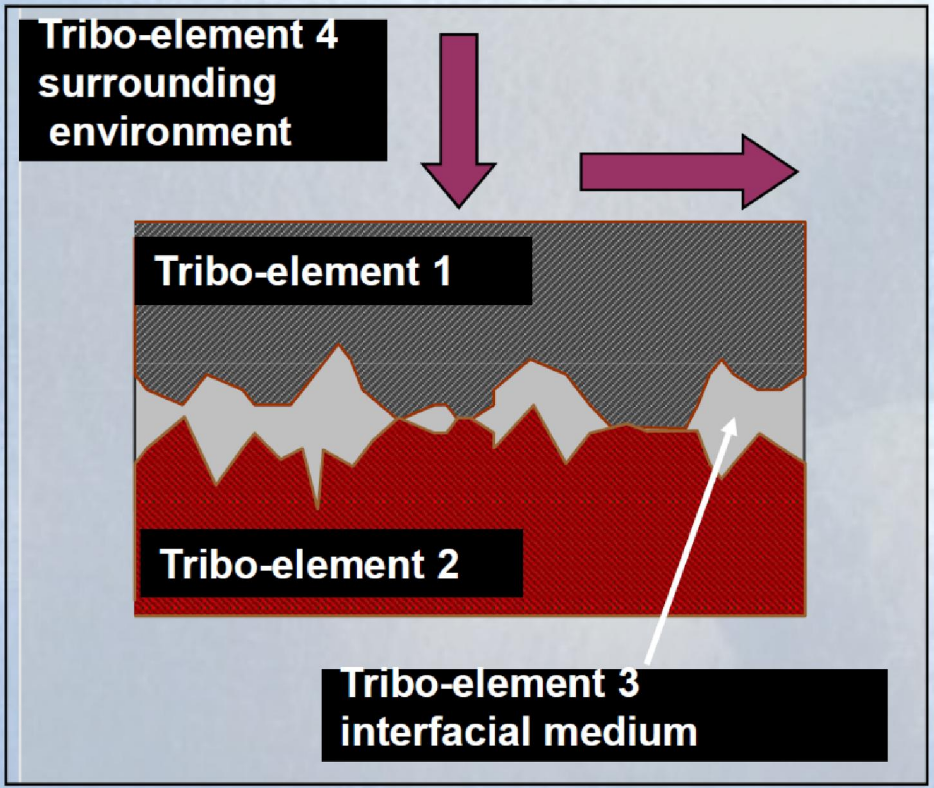
- In 1986 the development of the **Atomic Force Microscope** enabled scientists to study & understand friction at the atomic scale.

- 1980 onwards **Biolubricants** developments begin.

- 1990 onwards **Nanotribolgy, Biotribology** developments begin.

Basic

Tribo-system



Tribo-element 4
surrounding
environment

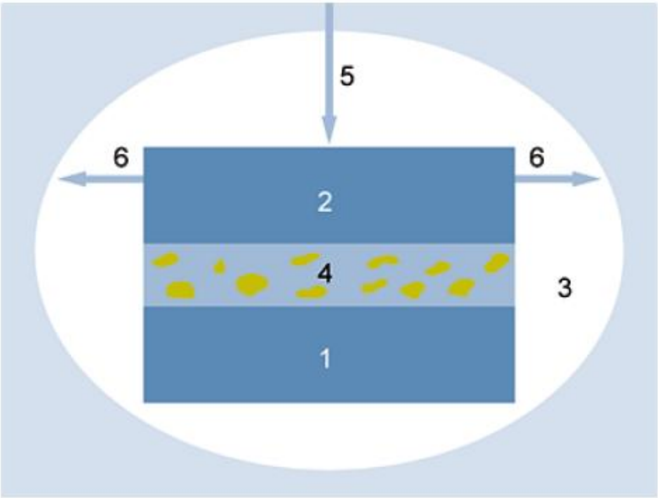
Tribo-element 1

Tribo-element 2

Tribo-element 3
interfacial medium

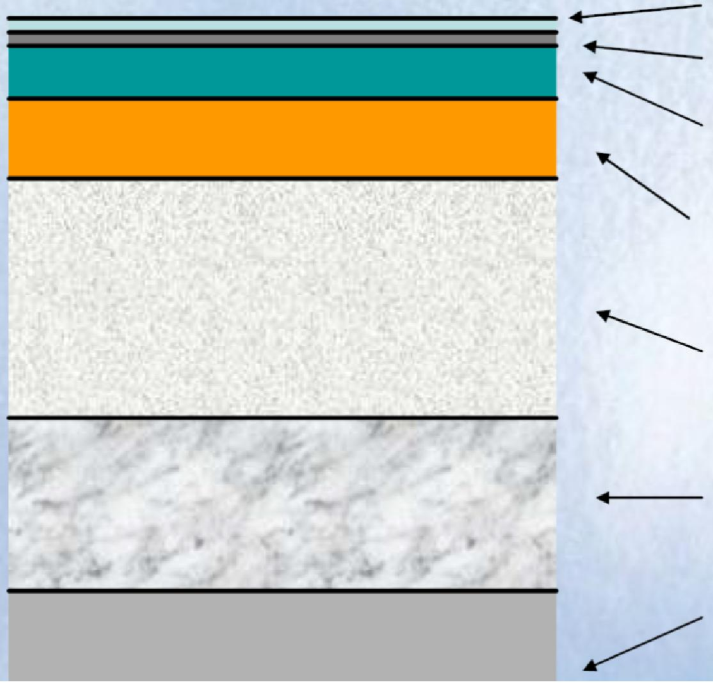
Tribological System

- A tribological system consists of the surfaces of two components that are in moving contact with one another and their surroundings. The type, progress and extent of wear are determined by the materials and finishes of the components, any intermediate materials, surrounding influences and operating conditions



1 Base object
2 Opponent body
3 Surrounding influences: Temperature, relative humidity, pressure
4 Intermediate material: Oil, grease, water, Particles, contaminants
5 Load
6 Motion

The Nature of Solid Surfaces



Physisorbed layer (0.3-3 nm)

Chemisorbed layer (0.3 nm)

Chemically reacted layer (10-100 nm)

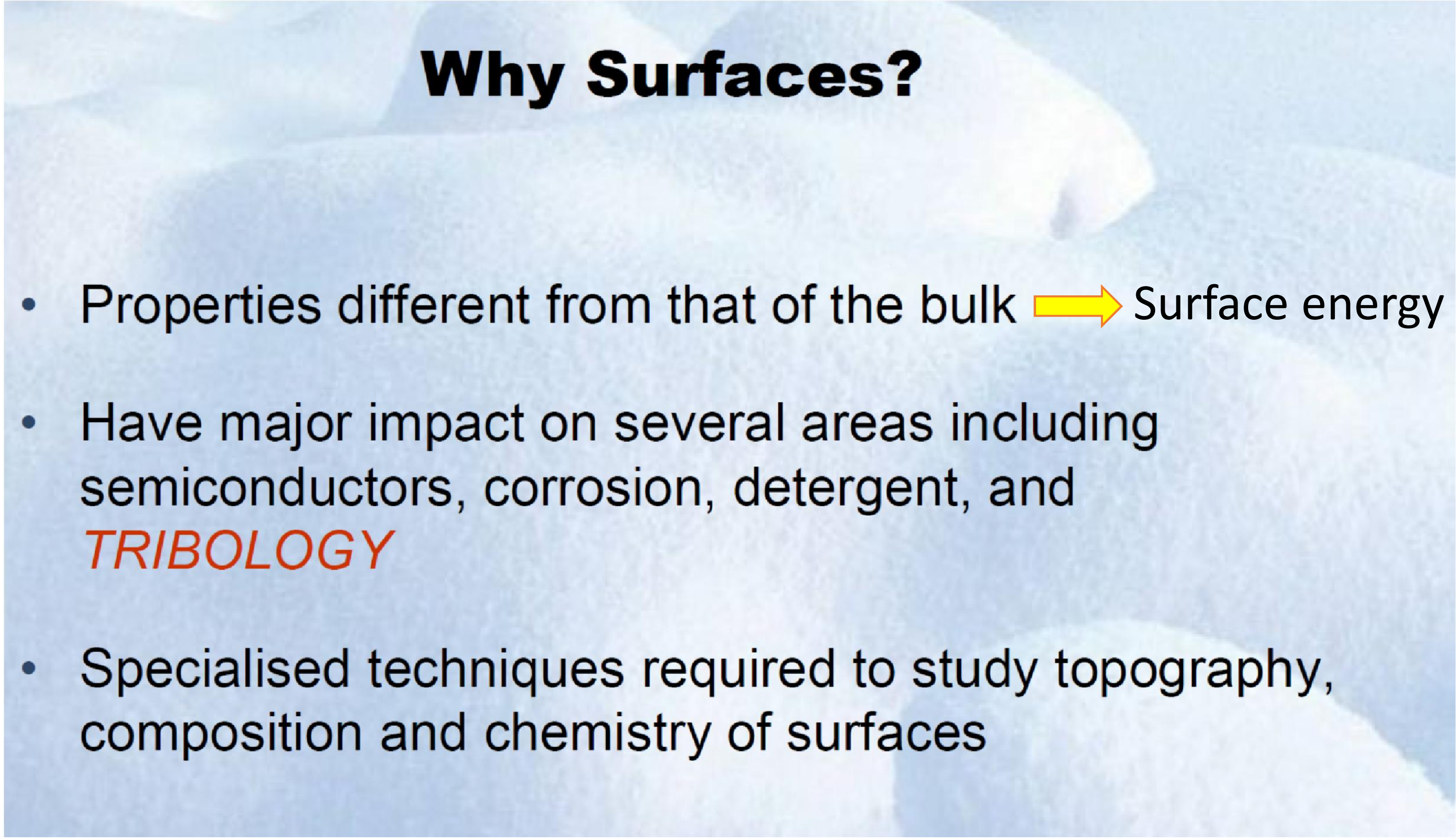
Beilby layer (1-100 nm)
(melted during machining)

Heavily deformed layer (1-10 μm)

Lightly deformed layer (1-10 μm)

Base material

Surface and roughness

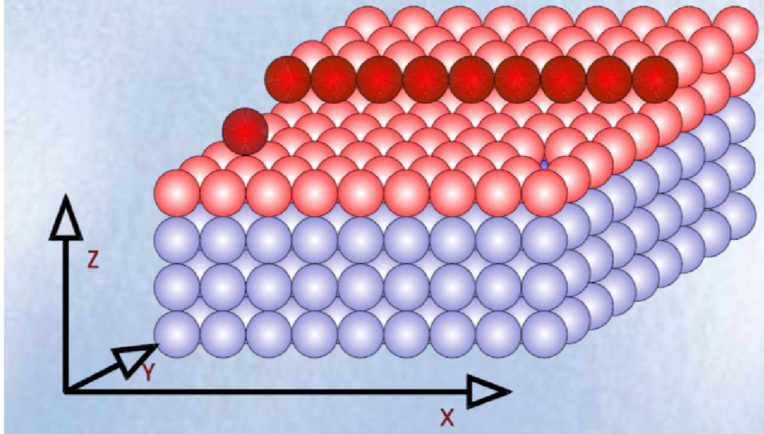


Why Surfaces?

- Properties different from that of the bulk → Surface energy
- Have major impact on several areas including semiconductors, corrosion, detergent, and *TRIBOLOGY*
- Specialised techniques required to study topography, composition and chemistry of surfaces

Surfaces

A surface is made by a sudden termination of the bulk structure. The bonding that was involved in the bulk lattice (for a solid) or liquid is severed to produce the interface.

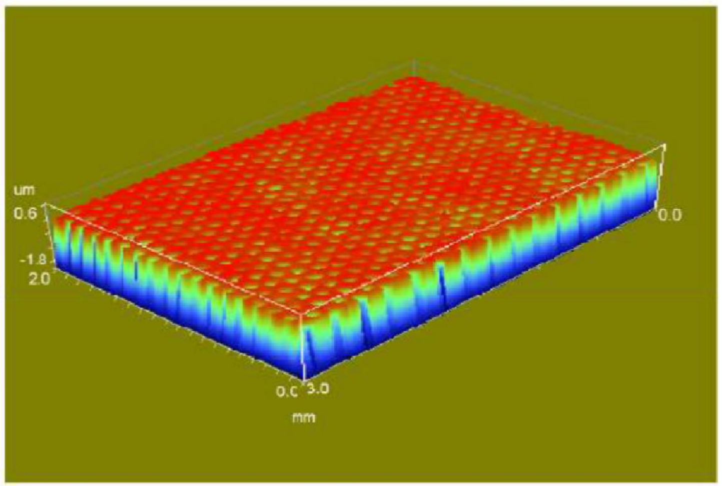


Since it requires energy to terminate the bonding, the surface is **energetically** less stable than the bulk.

This energy is known as the **surface free energy**. In the case of liquid interfaces, this energy is called **surface tension**.

Significance of Surfaces in Tribology

- friction
- wear
- effectiveness of lubricants
- surface defects and initiation of cracks
- thermal and electrical conductivities



Ra= 0.1987 μm, Rq= 0.304 μ m, Rz= 10.04 μ m

The force of static friction between two sliding surfaces is strongly dependent upon the real area of contact. Figure 6 below is a very crude representation of the profile between mating surfaces:

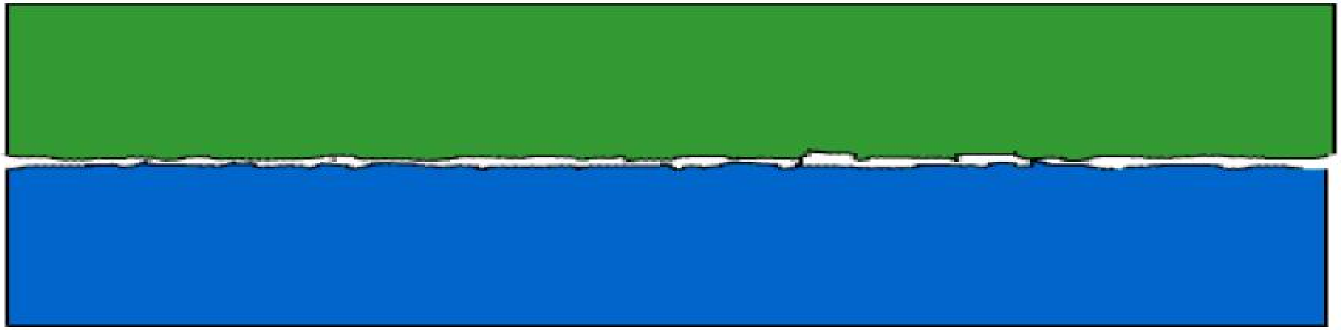
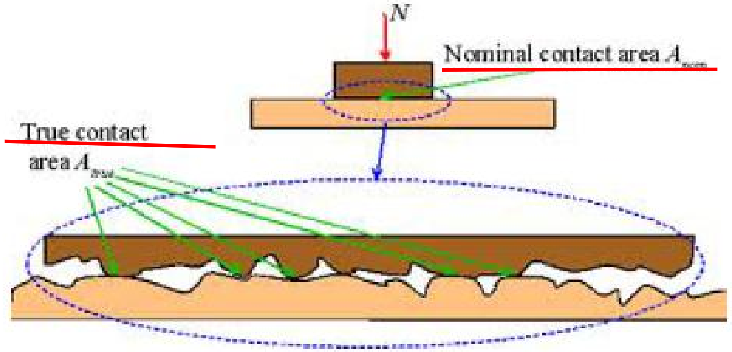


FIGURE 6: ASPERITIES OF MATING MACHINES SURFACES

Another representation



Surface Phenomenon

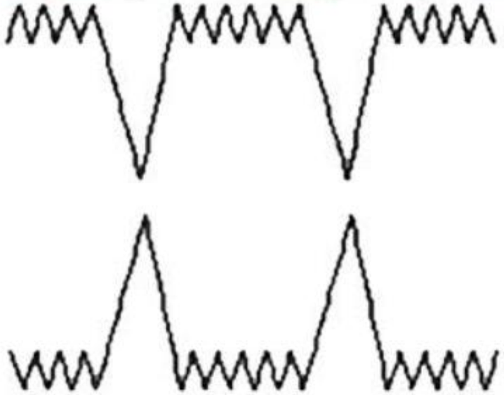
$$\sigma = \frac{F}{A}$$

- In tribology, motion under load induces stresses, which leads; elastic bending, breakage or ploughing of soft surface by asperities. It appears that *surface roughness* plays an important role in tribological phenomena.

- *Failure rate* of any tribo pair (two machine components in relative sliding motion) depends on the surface roughness of machine components

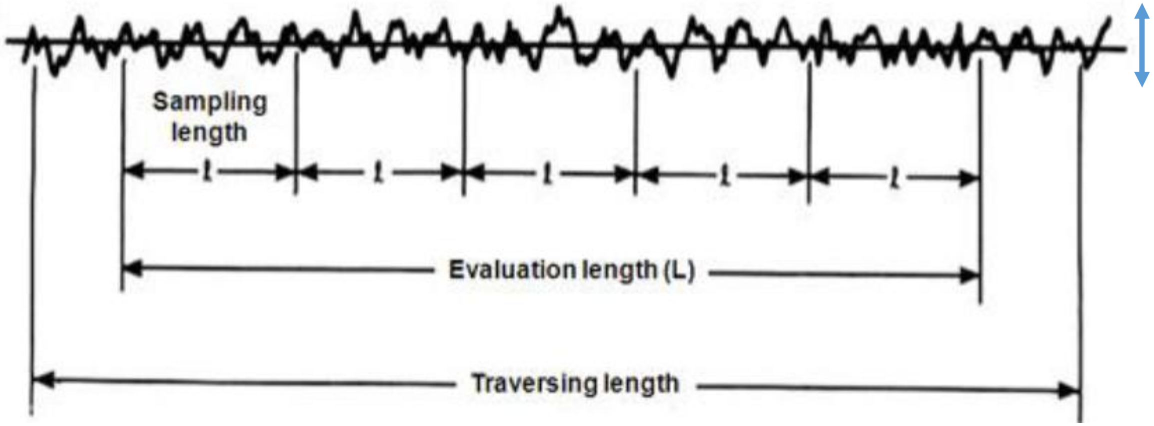
- Due to positive deviations (roughness above the nominal surface), the contact between solids confines to a very small fraction of nominally area (δA), and as a result estimated contact stress on rough surface = F/δA are much higher in magnitude compared to nominal stresses as expressed by following equation : Stress on smooth surface = F/A

Inverse surfaces with identical Ra(Average surface roughness) values

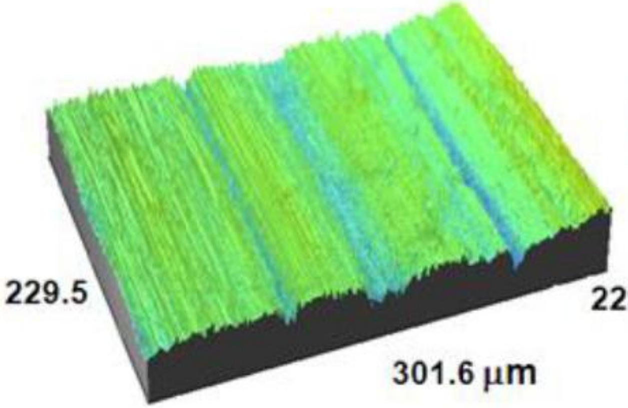


- Surface roughness is defined by short wavelength vertical deviations from nominal surface. Larger the deviations, rougher the surface. Fig. shows three different length: *Sampling length, evaluation length and traversing length*.

- This figure shows that traversing length is greater than evaluation length. This means we collect more sampling data and reject few data collected at the start and end of stylus. Further, to find statistically reliable surface roughness, averaging of roughness data over five sampling lengths is performed. Often roughness is quantified as average (R_a) and root mean square (R_q) roughness.

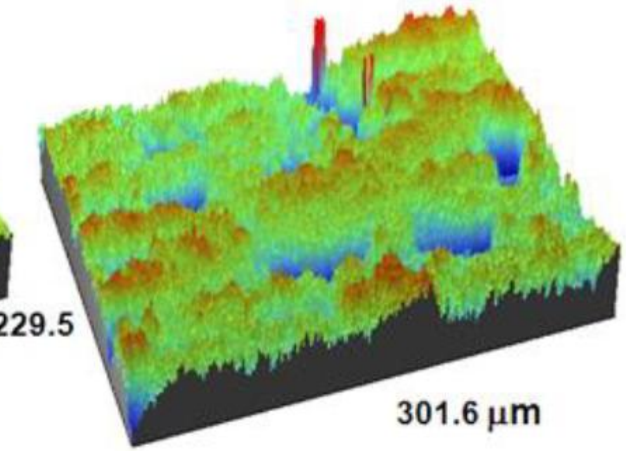


- Fig. shows too tribo-surfaces. If we compare R_a and R_q values of two images as shown in (a) and (b) respectively, we find *better performance* of (a) compared (b).
- In other words rough surfaces usually wear *more quickly* and have *higher friction coefficients* than smoother surface.



R_a : 451.61 nm
R_q : 597.96 nm

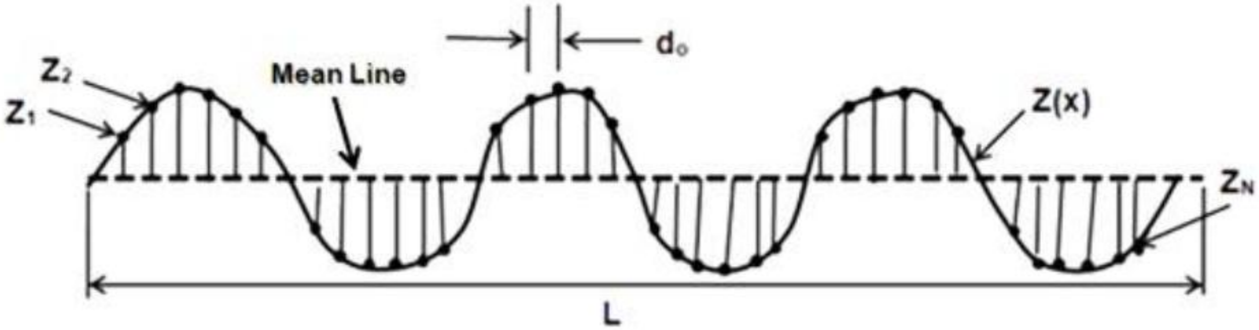
(a) Good Surface



R_a : 1.25 μm
R_q : 1.80 μm

(b) Bad Surface

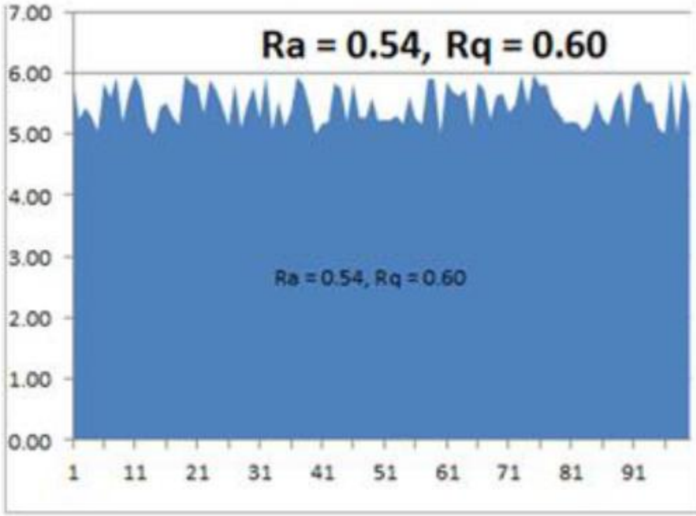
- Surface roughness is quantified by R_a and R_q values which can be calculated by *discrediting surfaces* as shown in Fig. in number of points.



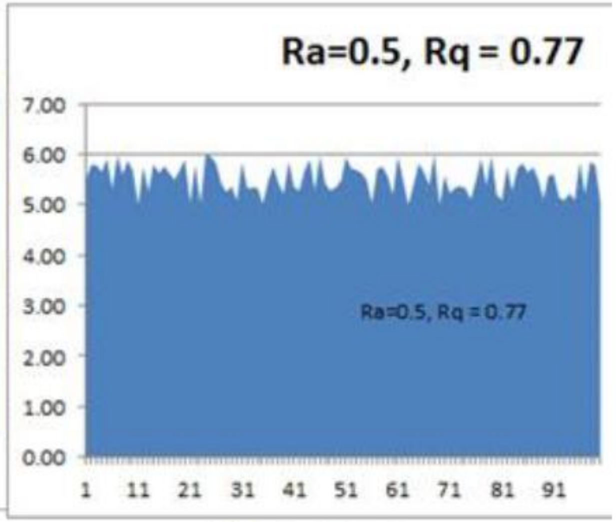
$$R_a = \left(|z_1| + |z_2| + \ldots |z_{N-1}| + |z_N|\right) / N$$

$$R_q = \sqrt{\left(\frac{z_1^2 + z_2^2 + \ldots z_{N-1}^2 + z_N^2}{N}\right)}$$

- From Tribology point of view R_q(root mean square) roughness is *preferred* over R_a(Average) roughness. Fig. (a) surface is treated as a good surface compared to surface shown in Fig. (b) due to lower value of R_q .
- This feature is often missed on comparing R_a value of two surfaces that is why comparing R_q values is *more important* than R_a values.



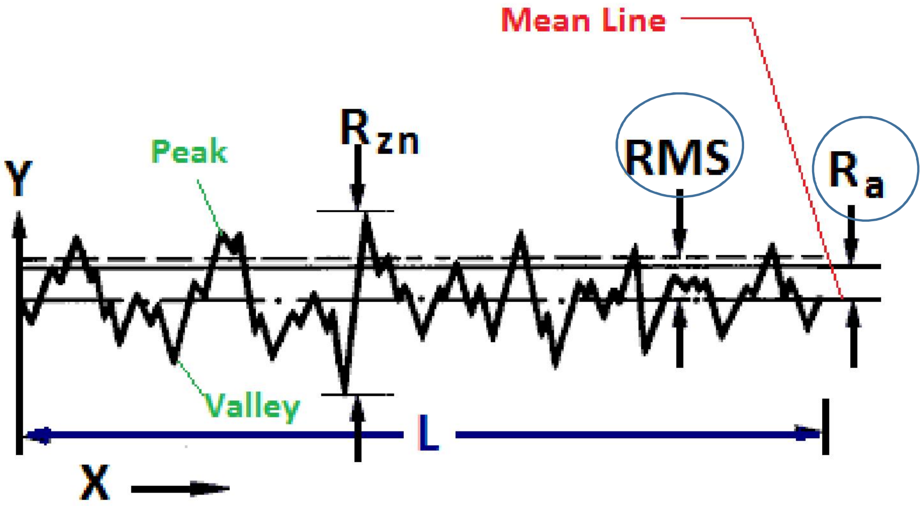
(a) Good Surface



(b) Bad Surface

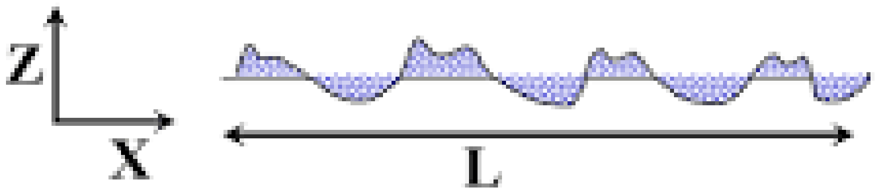
Numerical

- Take actual reading and calculate RA and RMS value of three different kind of surface of actual machine components.



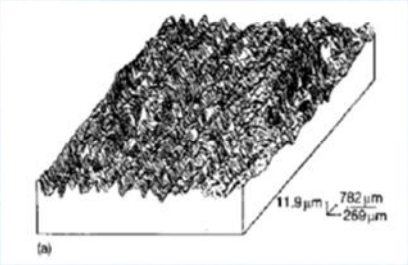
Ra (average roughness) measures the deviation of a surface from a mean height. The horizontal line through the profile represents the arithmetic mean height. The blue areas represent the deviations from that line.

Ra, then, is the total blue area divided by the length of the profile.

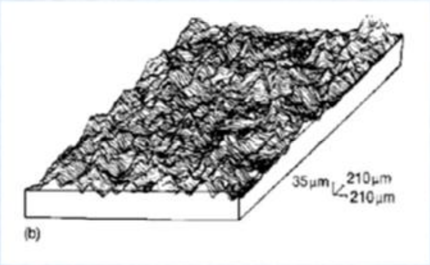


RMS is sensitive to larger peaks and valleys, where Ra is not

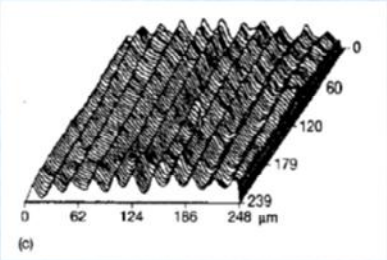
Contact of Rough Surfaces



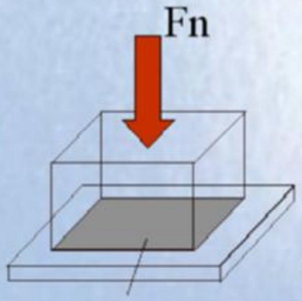
Ground
steel surface



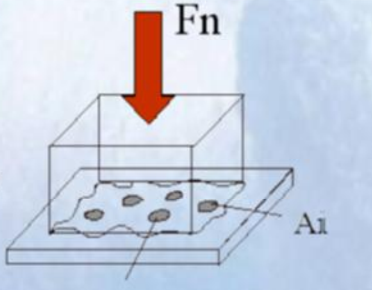
Shot-blasted
steel surface



Diamond
turned surface

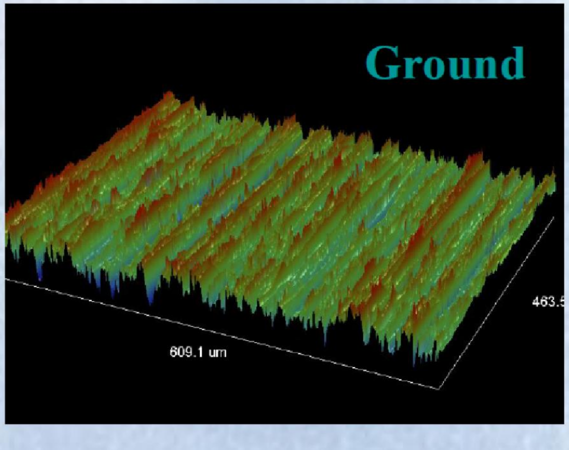


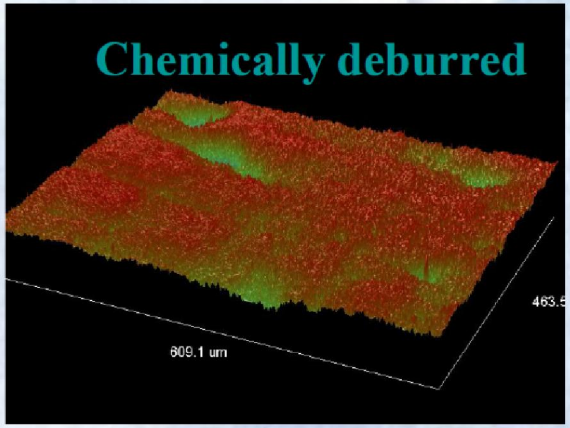
Apparent area
of contact

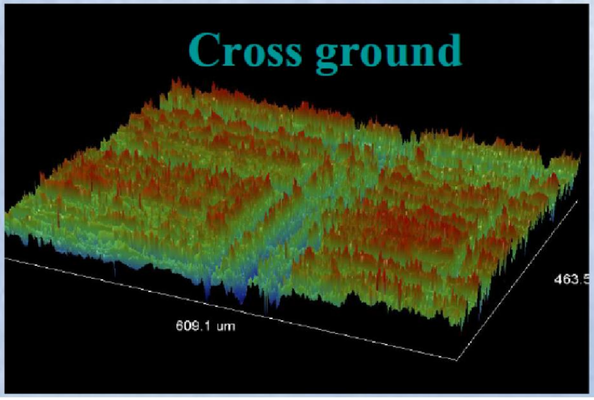


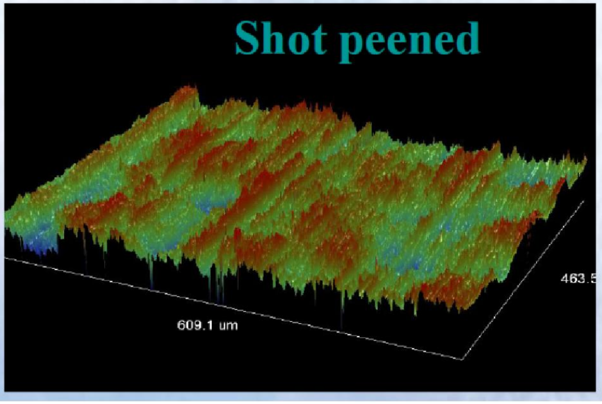
Real area
of contact

Surfaces Manufactured in Different Ways


Ground

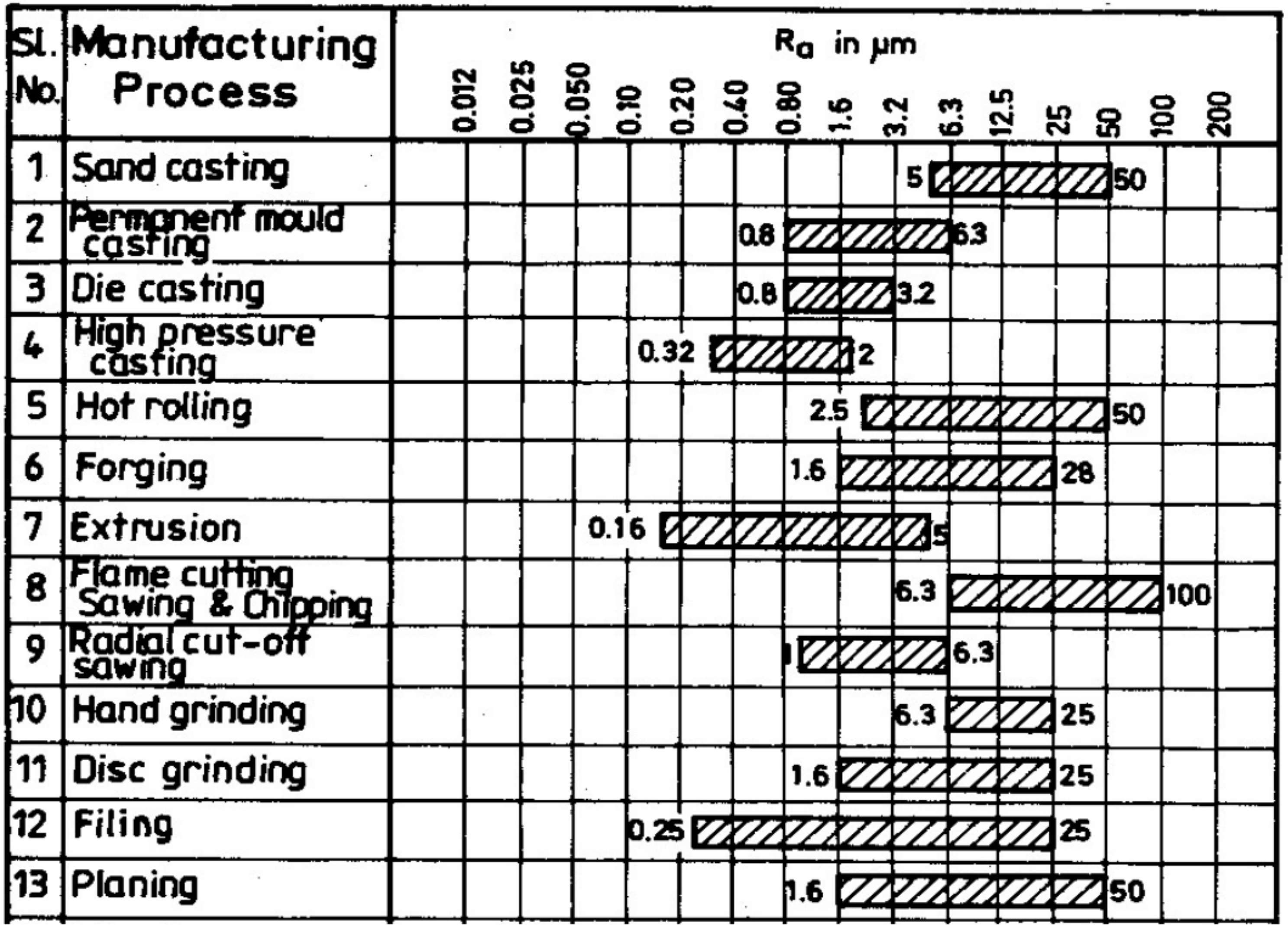

Chemically deburred


Cross ground

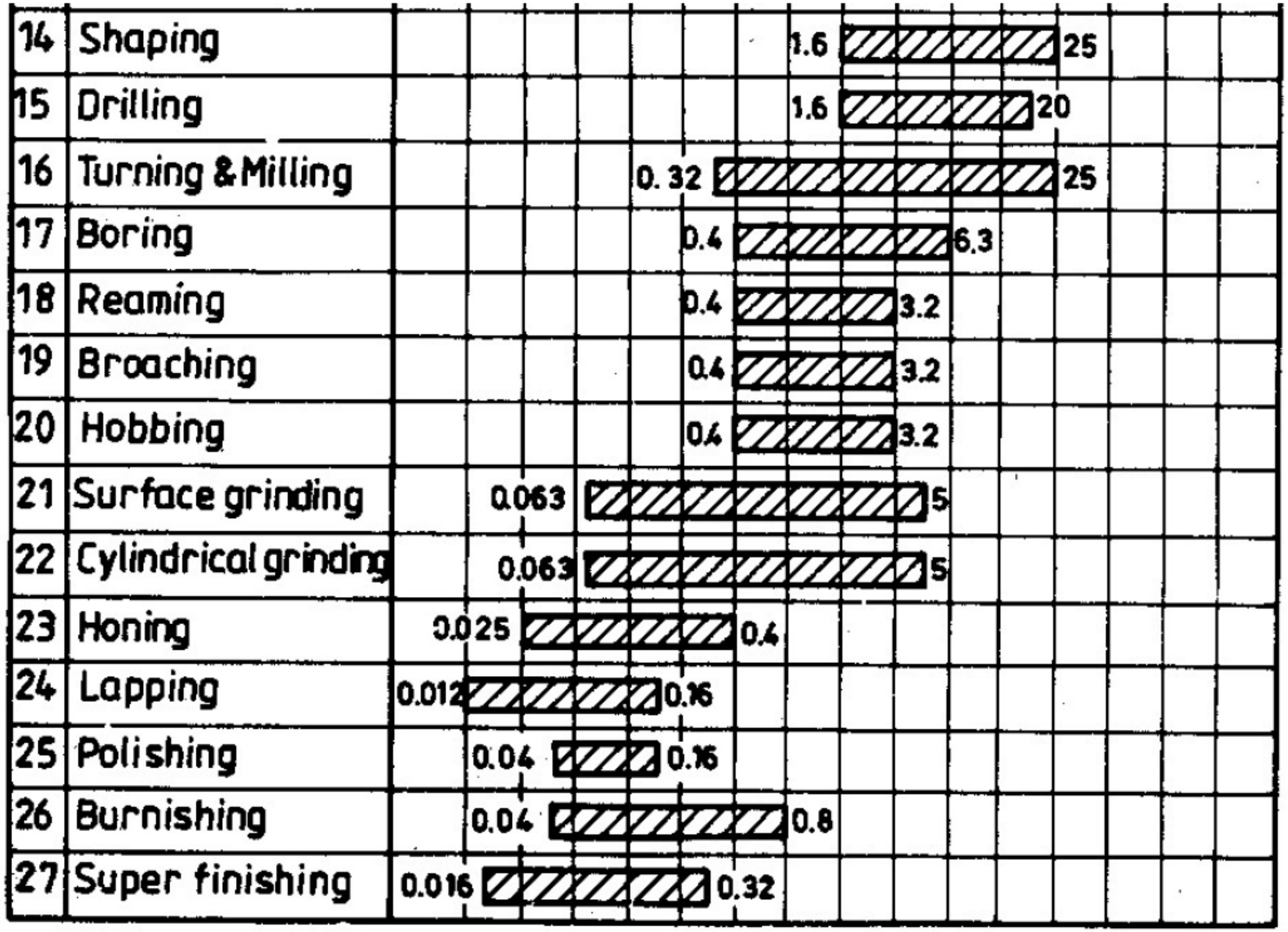

Shot peened

Typical Ra values for Engineering Surfaces

Process	Ra (μm)
Planing, shaping	*1-25*
Milling	*1-6*
Drawing, extrusion	*1-3*
Turning, boring	*0.4-6*
Grinding	*0.1-2*
Honing	*0.1-1*
Polishing	*0.1-0.4*
Lapping	*0.05-0.4*



Sl. No.	Manufacturing Process	Ra in µm	
1	Sand casting	5	50
2	Permanent mould casting	0.8	6.3
3	Die casting	0.8	3.2
4	High pressure casting	0.32	2
5	Hot rolling	2.5	50
6	Forging	1.6	28
7	Extrusion	0.16	5
8	Flame cutting Sawing & Chipping	6.3	100
9	Radial cut-off sawing	1	6.3
10	Hand grinding	6.3	25
11	Disc grinding	1.6	25
12	Filing	0.25	25
13	Planing	1.6	50


14 Shaping 1.6 25
15 Drilling 1.6 20
16 Turning & Milling 0. 32 25
17 Boring 0.4 6.3
18 Reaming 0.4 3.2
19 Broaching 0.4 3.2
20 Hobbing 0.4 3.2
21 Surface grinding 0.063 5
22 Cylindrical grinding 0.063 5
23 Honing 0.025 0.4
24 Lapping 0.012 0.16
25 Polishing 0.04 0.16
26 Burnishing 0.04 0.8
27 Super finishing 0.016 0.32

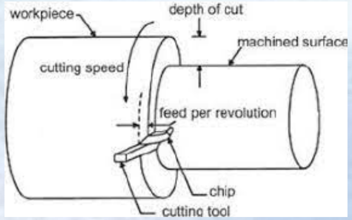
Surface Defects Caused During Manufacturing

- Crack
  internal/external
- Craters
- Folds/Seams/Laps
- Heat Affected Zone
  thermal cycling w/o melting
- Inclusions
- Residual stresses
- Splatter

- Intergranular attack
- Metallurgical transformations
  temp., press., cycling
- Plastic deformation
  worn tools
- Pits
  shallow surface depressions

The Origin of Surface Irregularities

- The production process
  - Turning
  - Grinding
  - Polishing



- The material structure
  - Brittleness
  - Atomic structure
- The use of the surfaces
  - Wear
  - Running-in
  - Corrosion

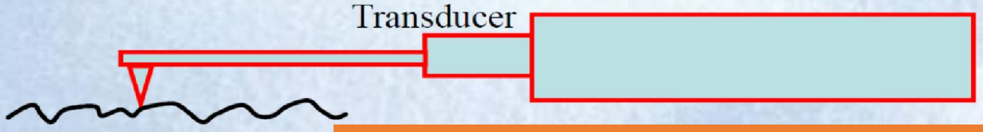
Surface Characterisation

- ❖ General features of surface
  - Appearance
  - Shape of surface
  - – Anisotropy ?
- ❖ Mechanical properties
  - Modulus
  - Yield Strength
  - Hardness
  - Toughness....
  - Stresses and strains
- ❖ Chemistry of surface
  - Elements present
  - Phase distribution

- ❖ **Localised defects**
  - Any local changes in
    - Shape
    - Mechanical properties
    - Chemistry
  - Cracks

Surface Topography Measurement Methods

- Stylus profilometers (2D+1D)



- Optical methods (3D)
  - Interferrometry
- Scanning probe microscopy (2D+1D)
  - Scanning tunneling microscopy (STM)
  - Atomic force microscopy (AFM)

Interferometry' is a measurement method using the phenomenon of interference of waves (usually light, radio or sound waves).

Surface topography measurements are never exact. All different Techniques give different answers. Even the use of the same technique at different laboratories!

AFM versus STM

- AFM provides high-resolution topographic images and information on sample mechanics, making it ideal for imaging delicate biological samples, polymers, and insulators.
- STM excels at atomic-scale electronic characterization of flat conductive surfaces like metals, semiconductors, or graphene.

Problems Encountered in Surface Topography Measurements

- **Stylus profilometers**
  - The tip radius (a few μm) is too large to resolve very fine irregularities
  - Might damage the surface (replication might be the solution)
- **Optical methods**
  - Expensive equipment
  - Thin films on the surface might cause errors
- **Scanning probe microscopy**
  - Expensive and sensitive equipment
  - Measurement on very small areas might lead to mis-interpretations

General Remarks

Considering the complexity of the tribological system, it may be pertinent to point out that friction and wear characteristics of materials are not their intrinsic or inherent properties but are highly system dependent.

Some of the Basic Questions
What is friction?

How is the friction force generated?

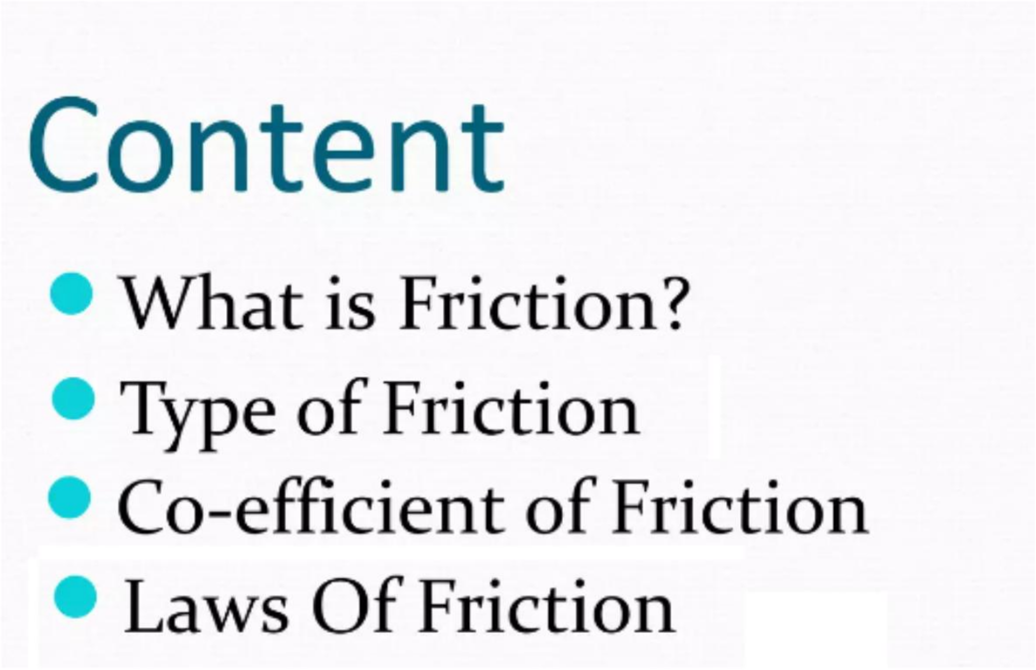
What is the coefficient of friction?

How do materials wear?

What is the effect of the applied load on friction and wear?
What is the role of lubricant?

How do you lower friction?
How should we reduce the wear rate of materials?

Friction

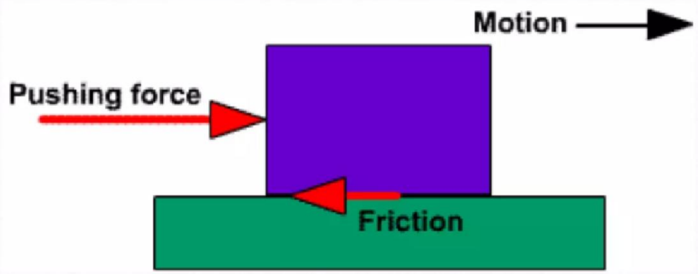


Content

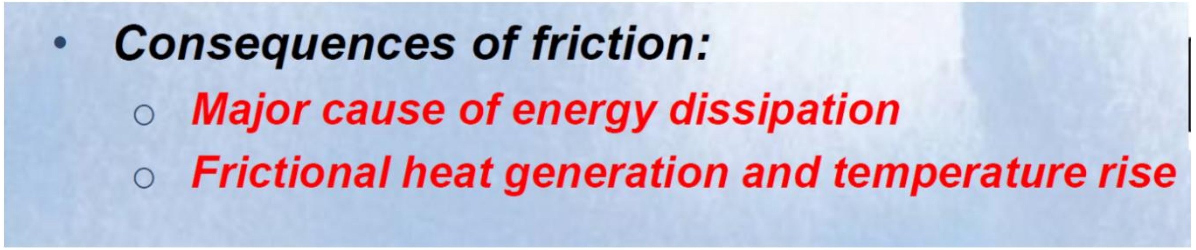
- What is Friction?
- Type of Friction
- Co-efficient of Friction
- Laws Of Friction

What Is Friction?

- When a body slide or tends to slide on a surface on which it is resting, a resisting force opposing the motion is produced at the contact surface. This resisting force is called friction or friction force.



- When one solid body is slide over another there is a resistance to the motion which is called friction.
- Considering friction as a nuisance, attempts are made to eliminate it or to diminish it to as small a value as possible.
- Considerable loss of power is caused by friction (e.g. about 20% in motor cars, 9% in airplane piston engine and (1 ½ -2)% in turbojet engines) but more important aspect is the damage that is done by friction – the WEAR of some vital parts of machines.
- This factor limits the design and shortens the effective working life of the machines.

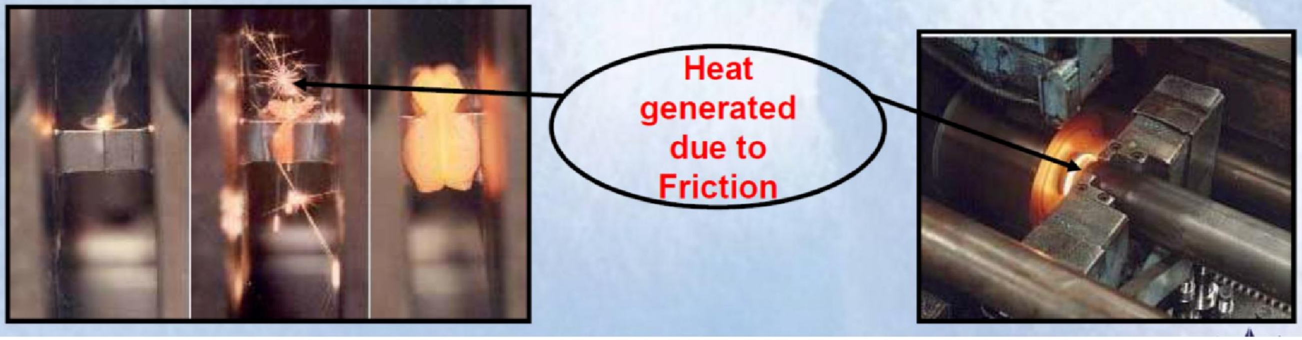


- ***Consequences of friction:***
  - ○ *Major cause of energy dissipation*
  - ○ *Frictional heat generation and temperature rise*

Friction

INTRODUCTION…..(Cont…)

- On the other hand, in most of running machines friction is undesirable (energy loss, leading to wear of vital parts, deteriorating performance due to heat generation) and all sorts of attempts (i.e. using low friction materials, lubricating surfaces with oil or greases, changing design so that sliding can be reduced) have been made to reduce it.



Heat generated due to Friction

- Many people think that it is a nuisance because it has causes us to apply a greater force to move an object.
- But in fact, it is of great help to us.

- **If there is no friction, then cars cannot move on the road and we can hardly even walk.**

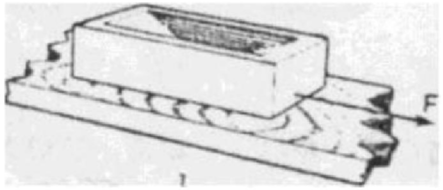
Friction

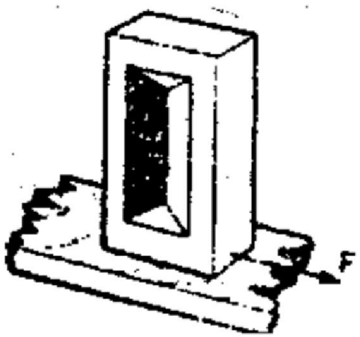
- ***We encounter friction in all aspects of everyday lives:***
- ***Walking***
- ***Moving***
- ***Stopping or turning a car***

❖ It is needed so that we have control on our walking.

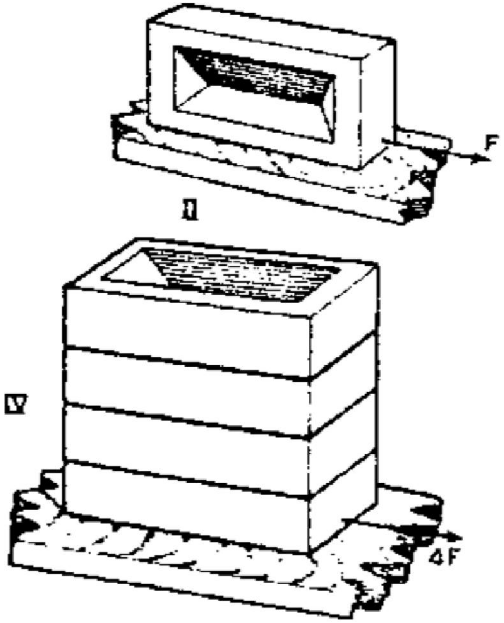
Laws of Friction

- First Law: The friction is independent of the area of contact between the solids .
- For example; if one pulls a brick along a table, the friction is same whether the brick is lying flat, or on its side, or standing on its end





- Second Law: The friction is proportional to the load between the surfaces
- e.g. if the load is doubled by putting a second brick on top of first, the force required to cause sliding is twice as great. If a pile of four bricks is used, the friction would be four times as great, and so on



Laws Of friction

- Laws of static friction
  - The friction force always acts in a direction, opposite to that in which the body tends to move.
  - The magnitude of friction force is equal to the external force.

$$F=P$$

  - The friction force does not depends upon the area of contact between the two surfaces.
  - The friction force depends upon the roughness of the surfaces.

What is friction?

- Friction is a result of energy dissipation at the (sliding) interface.

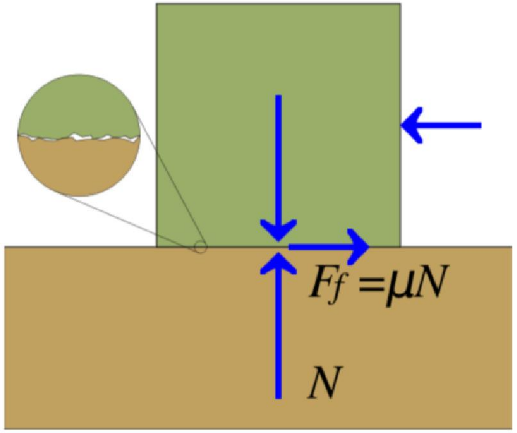
Friction force

$$f = \mu N$$

f = friction force

μ = coefficient of friction

N = normal force

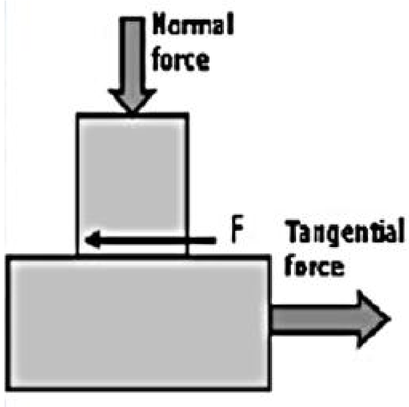


What is the coefficient of friction?

- Friction coefficient is defined as

μ = Friction / Load

$$\mu = \frac{\text{Tangential force}}{\text{Normal load}}$$



- Is it a material property?

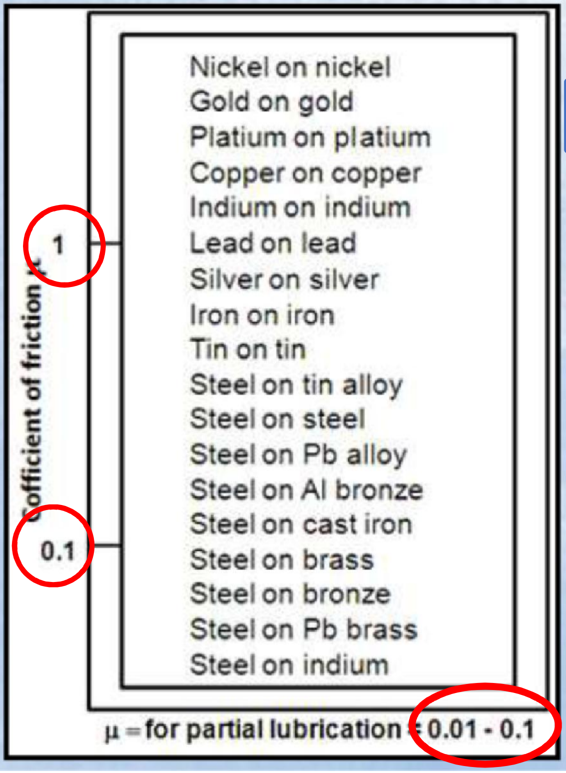
- It may be noted that μ varies widely for different solids.

- **Example:** For a case of a brick sliding over a clean wooden table μ = 0.5, i.e. force equal to one-half of the weight of the brick is required to pull it along.

  For ice sliding on ice, μ = 0.02 – 0.03 & For copper sliding over copper, μ = 0.8 to 1.0,

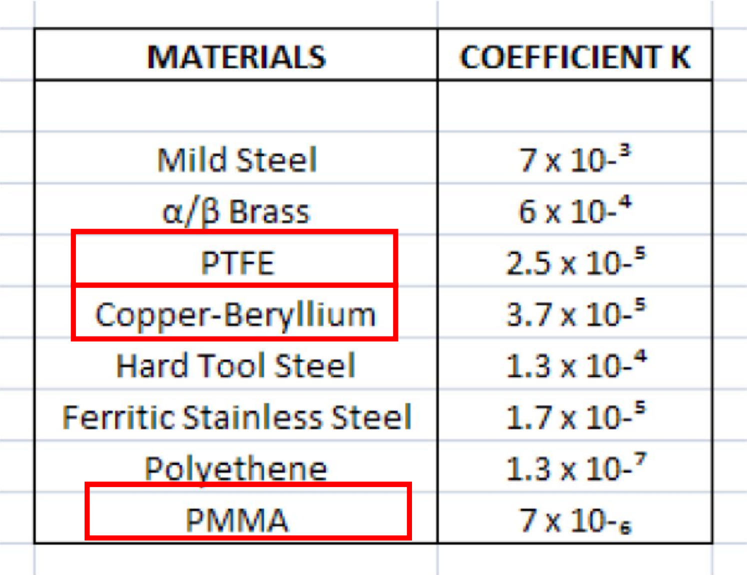
Friction

- Fig. indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.



For homework

Fig. : Coefficient of friction for various metals.



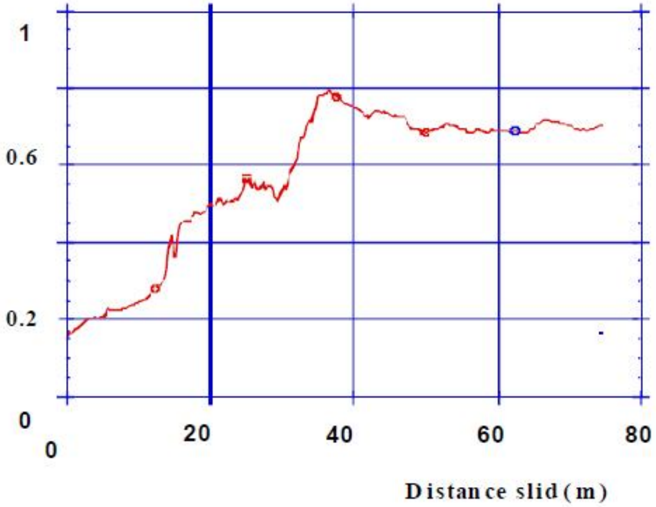
MATERIALS	COEFFICIENT K
Mild Steel	7 x 10-^{3}
α/β Brass	6 x 10-^{4}
PTFE	2.5 x 10-^{5}
Copper-Beryllium	3.7 x 10-^{5}
Hard Tool Steel	1.3 x 10-^{4}
Ferritic Stainless Steel	1.7 x 10-^{5}
Polyethene	1.3 x 10-^{7}
PMMA	7 x 10-$_{6}$

Polymethyl methacrylate

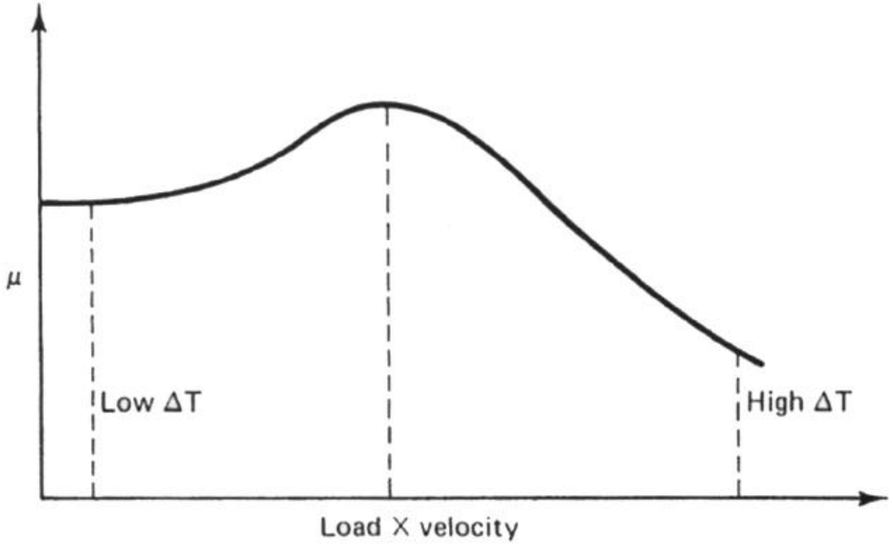
TABLE 2: COEFFICIENT OF WEAR (ω) FOR VARIOUS MATERIALS

Experimental facts characterize the friction of sliding solids:

Is the friction coefficient constant?

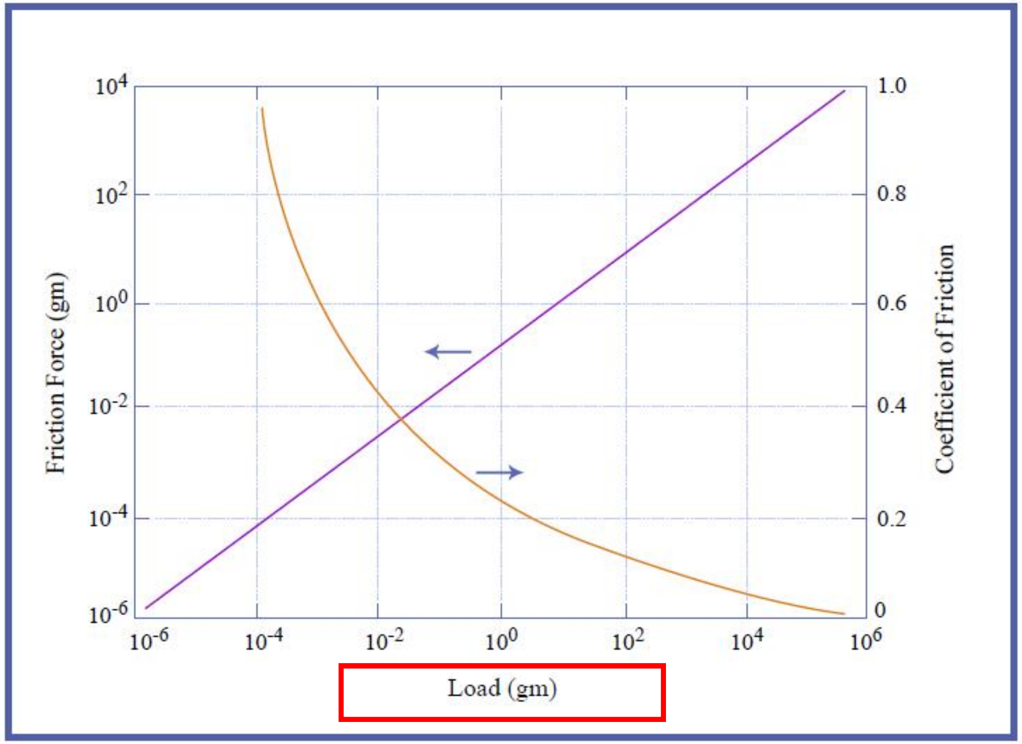


Is the friction coefficient constant?



Source: Figure 1.1, Suh (1986)

Is the friction coefficient constant?



Is the friction coefficient constant?

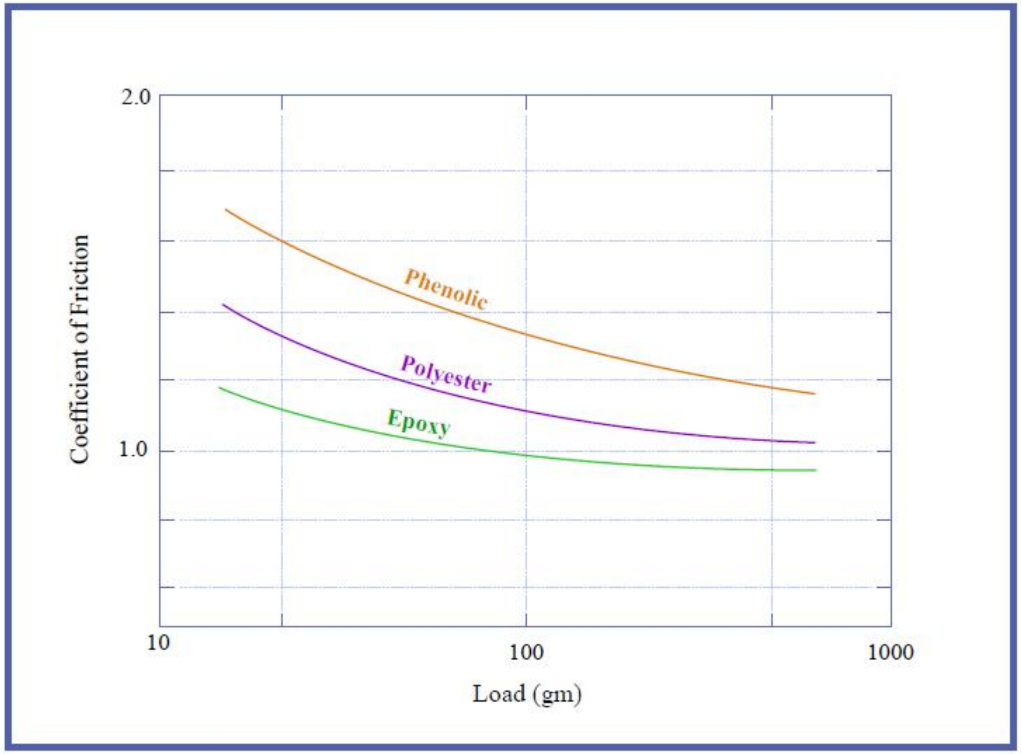


Figure by MIT OCW. After Pinchibeck, P. H. "A Review of Plastic Bearings." *Wear* 5 (1962): 85-113.

Is the friction coefficient constant?

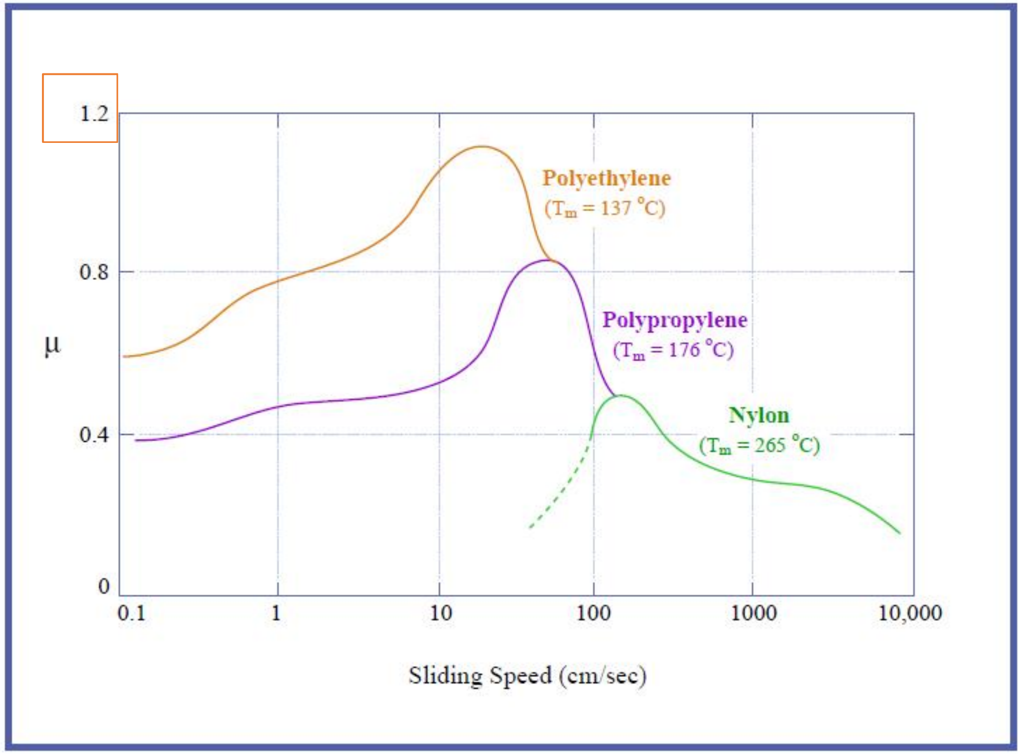


Figure by MIT OCW. After McLaren and Tabor, 1963.

Types of friction:

- Dry friction
- Fluid friction
- Lubricated friction
- Skin friction (Fluid and solid)
- Internal friction (Solids)

Dry or
Coulombic
friction

Types of Friction

- Static
- Sliding
- Rolling
- Fluid

Static and Kinetic Friction

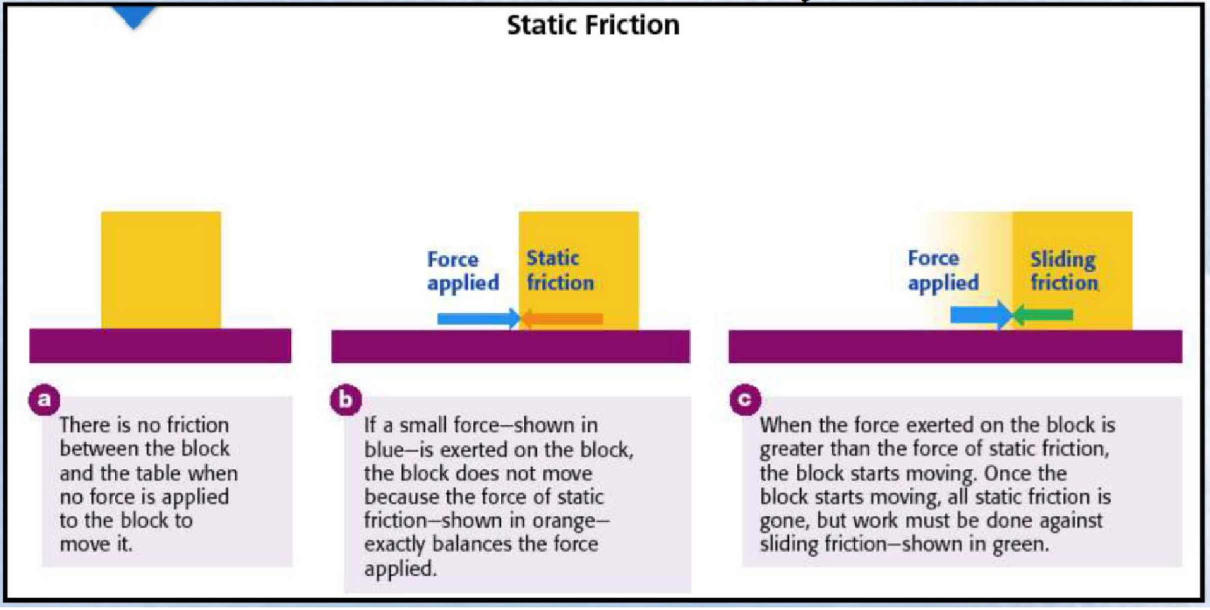
- Static friction is the force required to start sliding.

Dynamic Friction

- kinetic friction is the force required to maintain it.
- It is known that kinetic friction is less than the static friction and kinetic friction is nearly independent of the speed of sliding.

Static Friction

- In this figure, a horizontal force is applied to a body with an intention to move it to the right-side. (note: if the force applied is too small the “static friction is greater and the block will not move.)



Static Friction

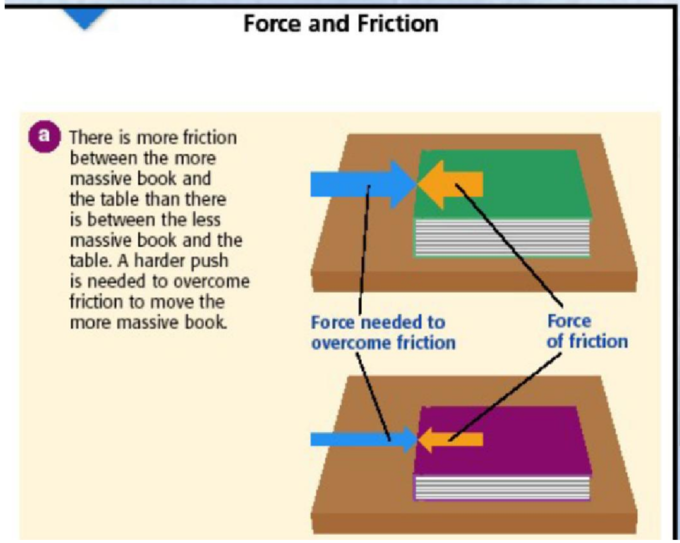
a There is no friction between the block and the table when no force is applied to the block to move it.

b If a small force—shown in blue—is exerted on the block, the block does not move because the force of static friction—shown in orange—exactly balances the force applied.

c When the force exerted on the block is greater than the force of static friction, the block starts moving. Once the block starts moving, all static friction is gone, but work must be done against sliding friction—shown in green.

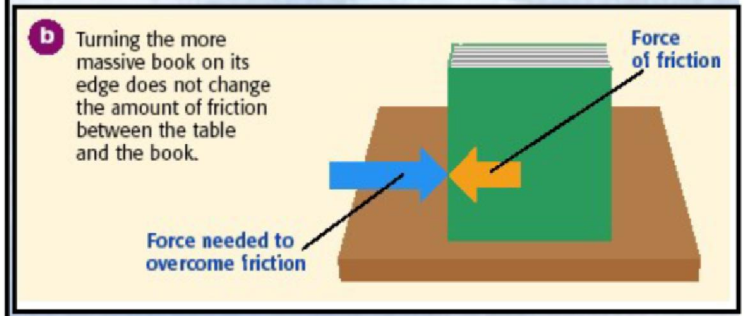
Greater Mass
Creates More Friction

A greater push is needed to overcome the greater mass which has greater (static) friction

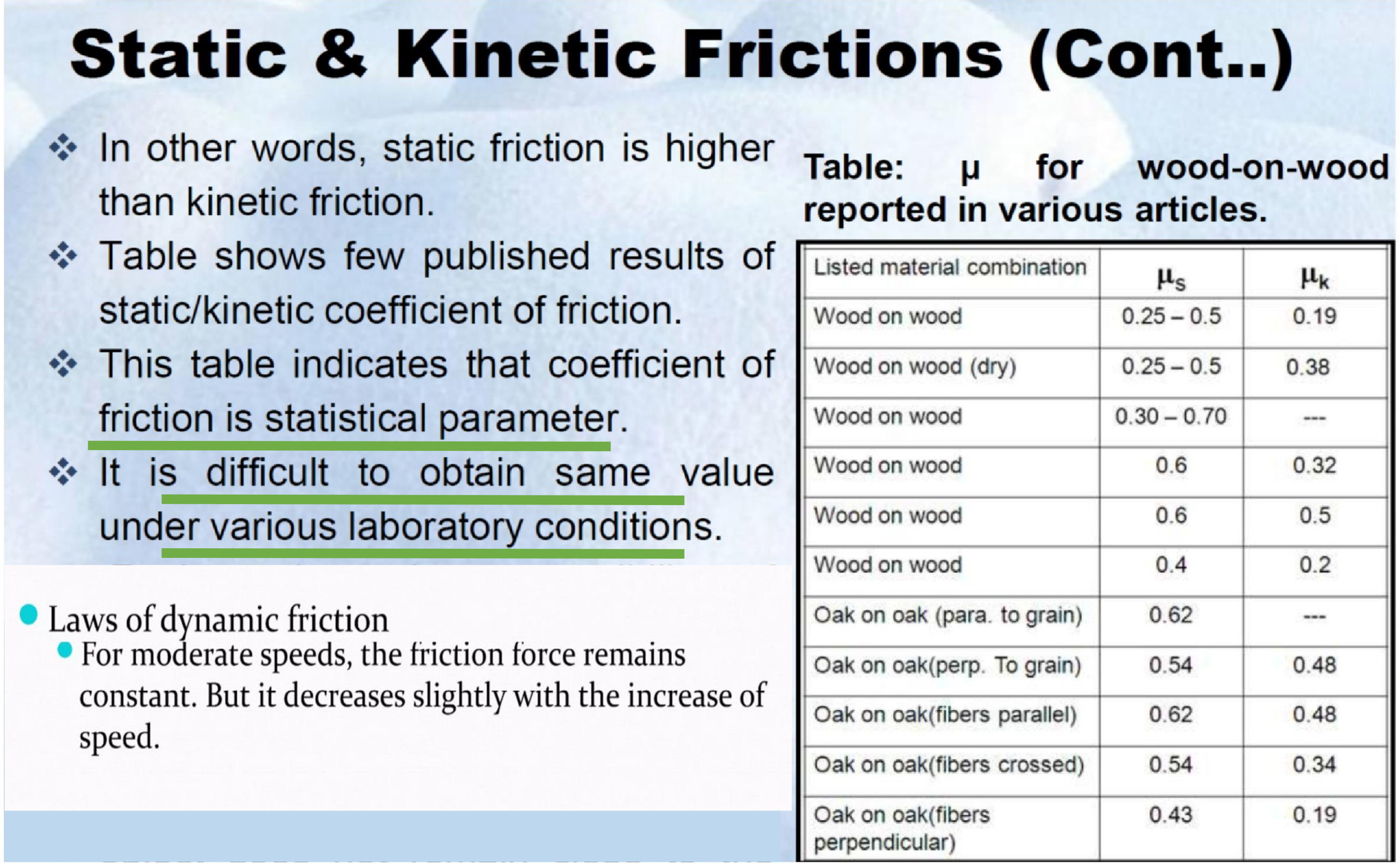


Force and Friction

a There is more friction between the more massive book and the table than there is between the less massive book and the table. A harder push is needed to overcome friction to move the more massive book.



b Turning the more massive book on its edge does not change the amount of friction between the table and the book.



Static & Kinetic Frictions (Cont..)

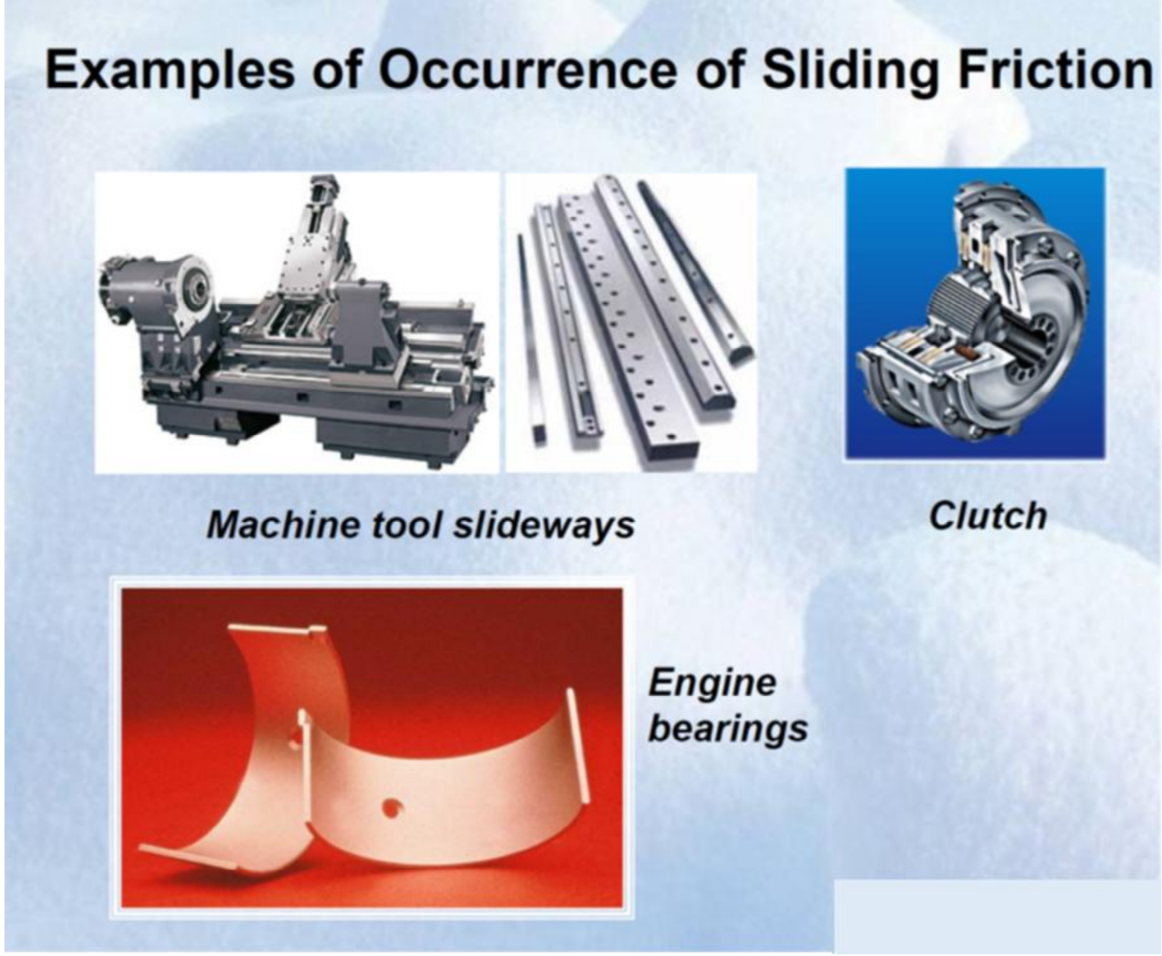
- In other words, static friction is higher than kinetic friction.
- Table shows few published results of static/kinetic coefficient of friction.
- This table indicates that coefficient of friction is statistical parameter.
- It is difficult to obtain same value under various laboratory conditions.

- Laws of dynamic friction
  - For moderate speeds, the friction force remains constant. But it decreases slightly with the increase of speed.

Table: μ for wood-on-wood reported in various articles.

Listed material combination	μ_s	μ_k
Wood on wood	0.25 – 0.5	0.19
Wood on wood (dry)	0.25 – 0.5	0.38
Wood on wood	0.30 – 0.70	---
Wood on wood	0.6	0.32
Wood on wood	0.6	0.5
Wood on wood	0.4	0.2
Oak on oak (para. to grain)	0.62	---
Oak on oak(perp. To grain)	0.54	0.48
Oak on oak(fibers parallel)	0.62	0.48
Oak on oak(fibers crossed)	0.54	0.34
Oak on oak(fibers perpendicular)	0.43	0.19

Sliding and rolling



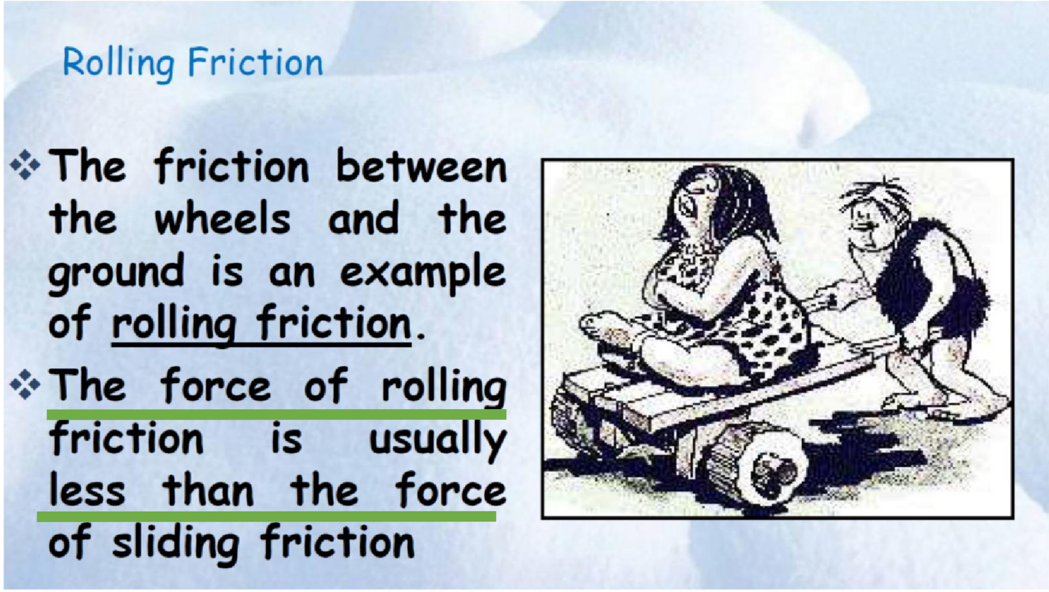
Examples of Occurrence of Sliding Friction

Machine tool slideways

Clutch

Engine bearings

Sliding and rolling



Rolling Friction

- The friction between the wheels and the ground is an example of rolling friction.
- The force of rolling friction is usually less than the force of sliding friction

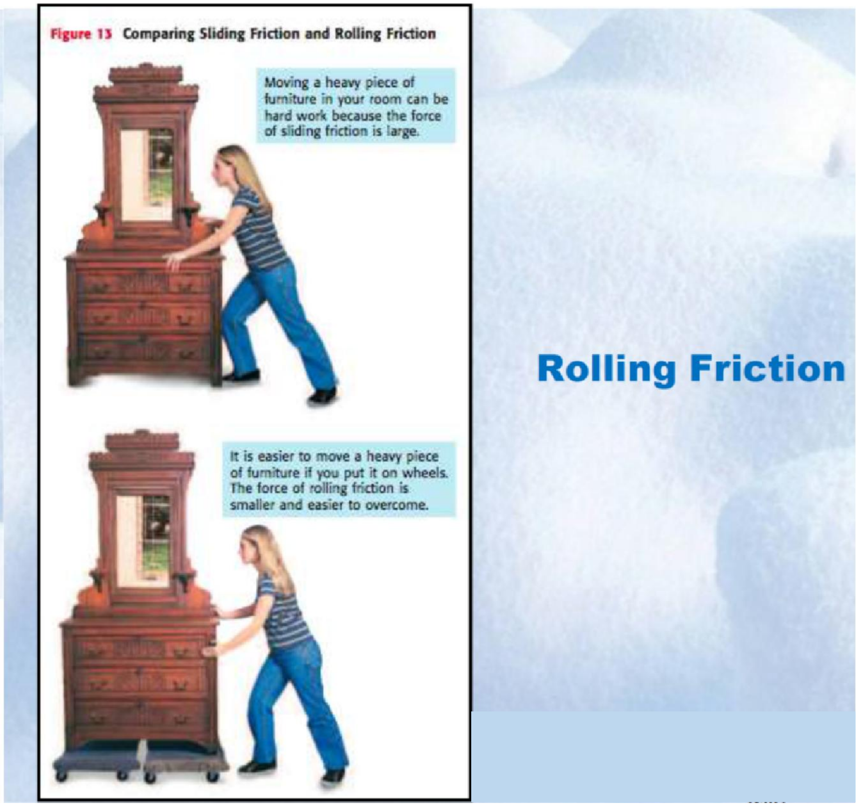


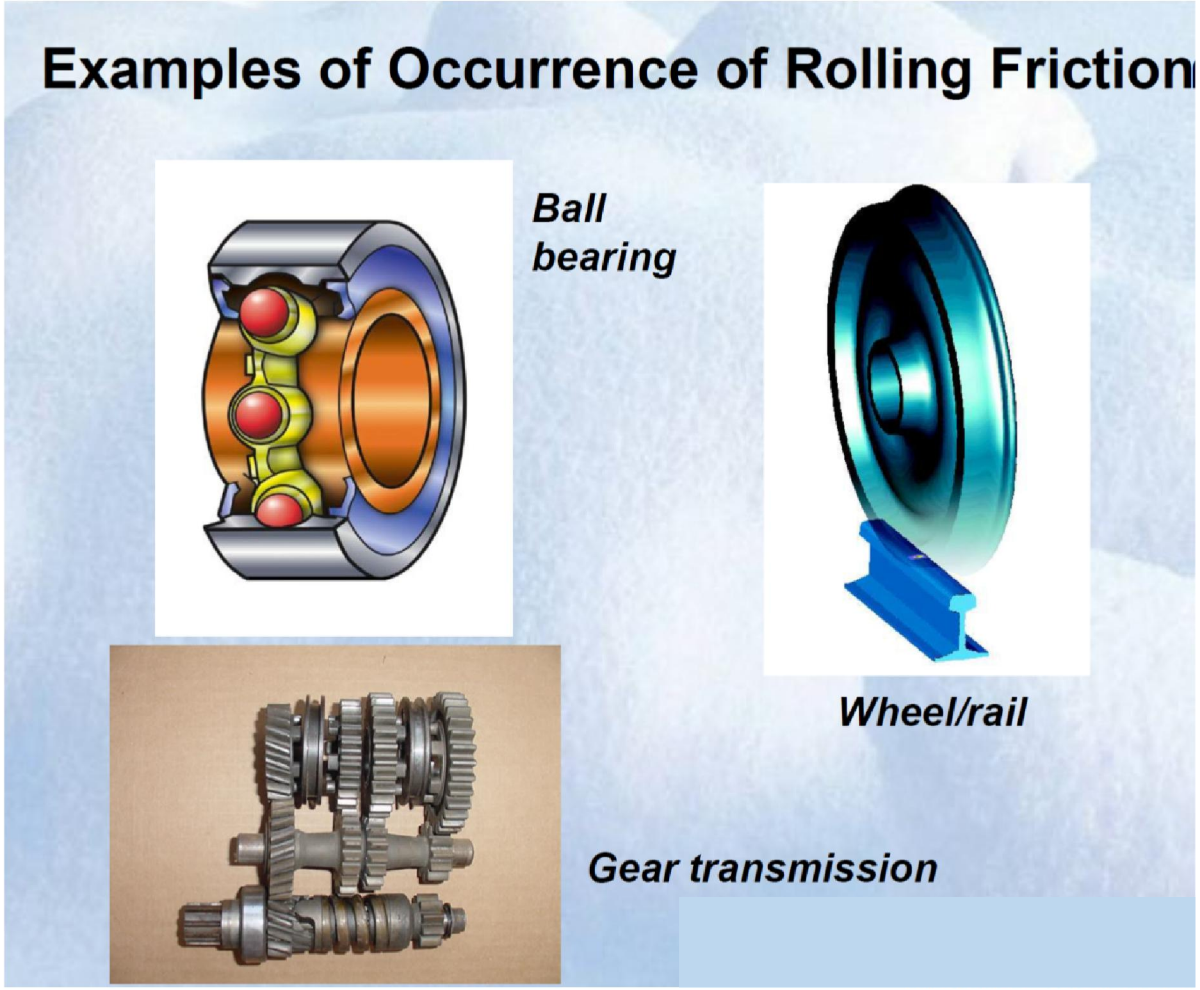
Figure 13 **Comparing Sliding Friction and Rolling Friction**

Moving a heavy piece of furniture in your room can be hard work because the force of sliding friction is large.

It is easier to move a heavy piece of furniture if you put it on wheels. The force of rolling friction is smaller and easier to overcome.

Rolling Friction

Sliding and rolling



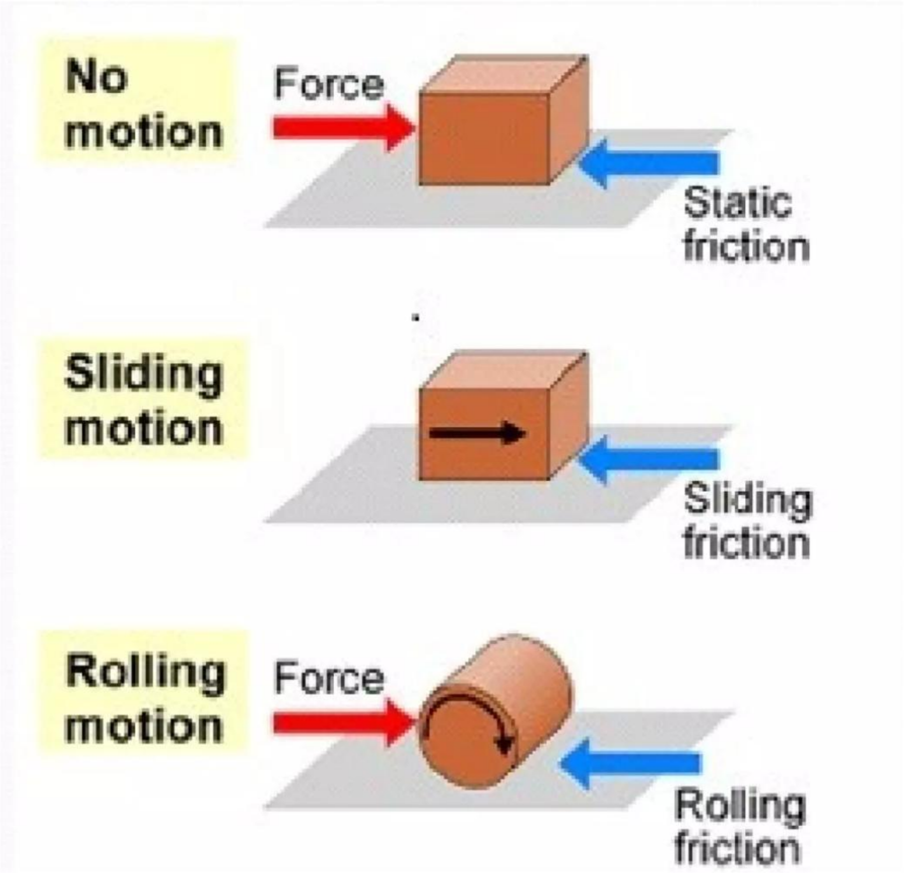
Examples of Occurrence of Rolling Friction

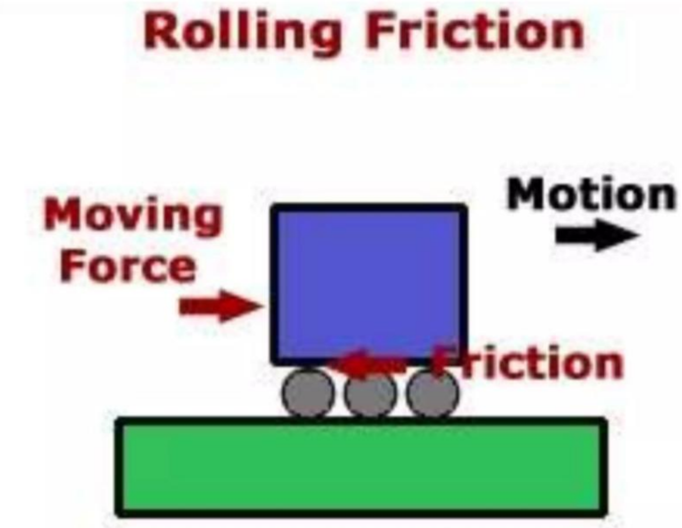
Ball bearing

Wheel/rail

Gear transmission

Sliding and rolling



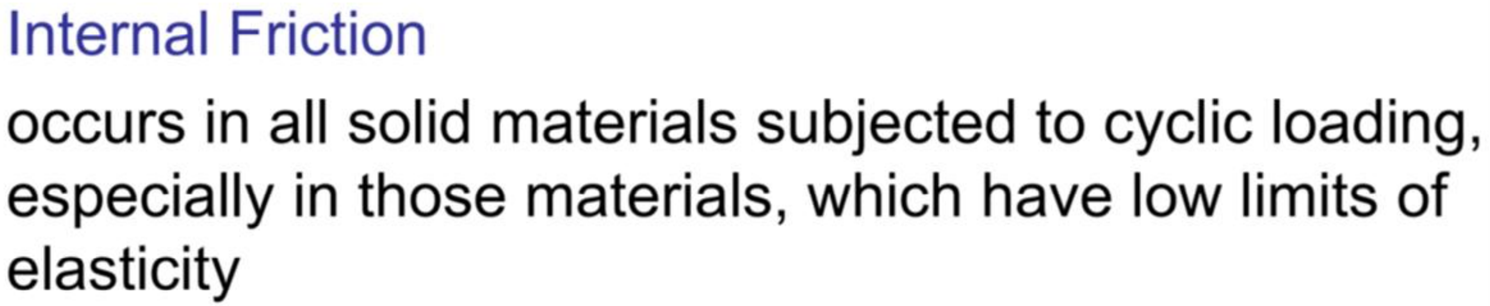


ROLLING FRICTION

- Other than sliding, an other way in which surfaces can move over one another is rolling, and it is much easier to roll surfaces along than to slide them.

Types of Rolling :

- The first type of rolling occurs when a car wheel is driven over a road or a train wheel over a rail. Here considerable tangential forces are involved in pulling the vehicle along, and the conventional frictional grip between the wheel and the surface is of great importance.
- The other type of rolling involves only a minute tangential traction i.e. the rolling that occurs when a ball or cylinder rolls freely over another surface called free rolling which is most commonly applied in ball bearings and roller bearings. The resistance in these cases is phenomenally low (≤ 0.001).



Internal Friction

occurs in all solid materials subjected to cyclic loading, especially in those materials, which have low limits of elasticity

Internal friction is a force that occurs within an object. It involves the maintenance of particles forming a material that remains in the same location in relation to one another.

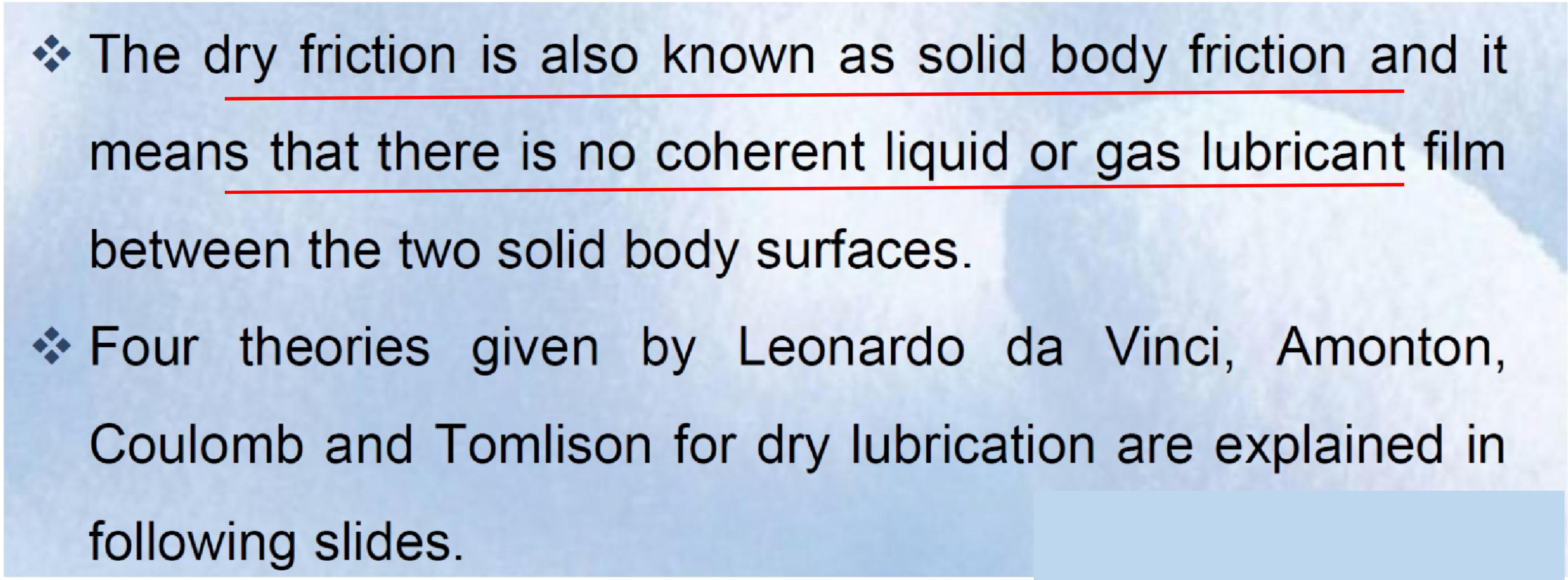
Fluid Friction

- Fluid friction opposes the motion of objects traveling through a fluid

- Remember that fluids include liquids & gases, water, milk and air are ALL fluids

Figure 14 *Swimming provides a good workout because you must exert force to overcome fluid friction.*

Dry and wet



- The dry friction is also known as solid body friction and it means that there is no coherent liquid or gas lubricant film between the two solid body surfaces.
- Four theories given by Leonardo da Vinci, Amonton, Coulomb and Tomlison for dry lubrication are explained in following slides.

Theories on Friction (Cont..)

- ***Leonardo da vinci(Earliest experimenter, 1452-1519) :***

As per Leonardo, “Friction made by same weight will be of equal resistance at the beginning of movement, although contact may be of different breadths or length”.

“Friction produces the double the amount of effort if weight be doubled”.

In other words, F α W.

Theories on Friction (Cont..)

- ***G. Amontons, 1699 :*** The friction force is independent of the nominal area (F ≠ A) of contact between two solid surfaces. The friction force is directly proportional F α N to the normal component of the load. He considered three cases (Fig.) and showed that friction force will vary as per the angle of application of load. As per Amontons μ = 0.3 for most of materials.

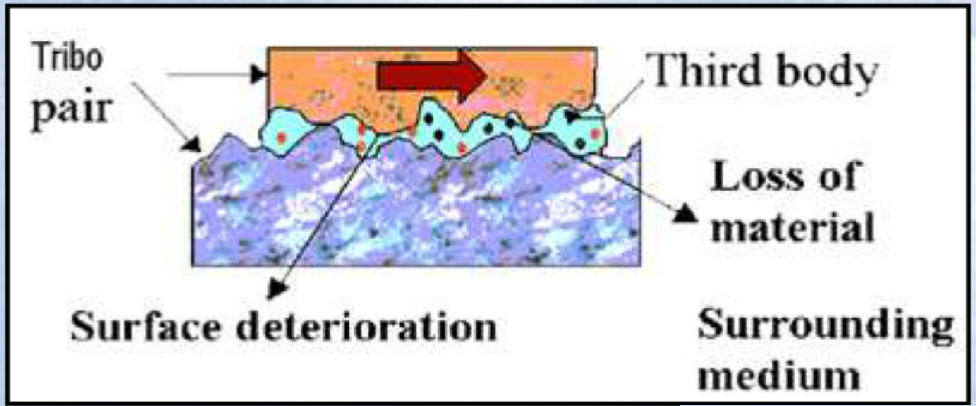


Fig. : Amonton`s work

Theories on Friction (Cont..)

- ***C.A. Coulomb 1781 (1736-1806) :***

✓ Clearly distinguished between static & kinetic frictions. Friction due to interlocking of rough surfaces.

Contact at discrete points μstatic ≥ μkinetic.

f ≠ func(A).

f ≠ func(v).

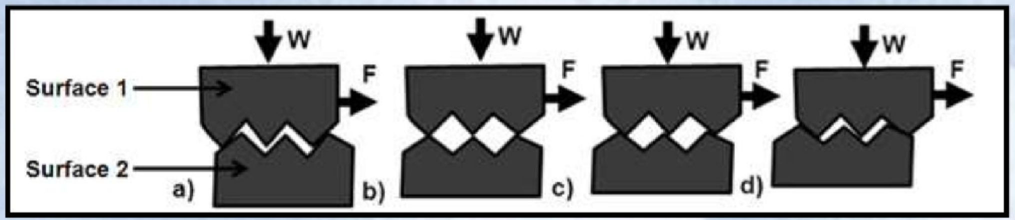


Fig. : Coulomb friction model.

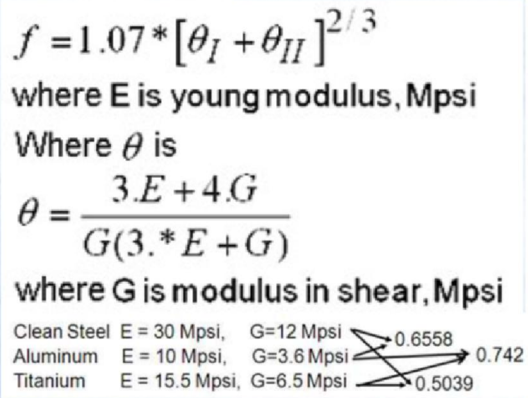
✓ As per coulomb friction force is independent of sliding speed. But this law applies only approximately to dry surfaces for a reasonable low range of sliding speeds, which depends on heat dissipation capabilities of tribo-pairs.

Theories on Friction (Cont..)

- ***TOMLINSON's Theory of Molecular attraction, 1929 :***

  Tomlison based on experimental study provided relation between friction coefficient & elastic properties of material involved.

- As per Tomlison due to molecular attraction between metal, cold weld junctions are formed. Generally load on bearing surface is carried on just a few points. These are subjected to heavy unit pressure, and so probably weld together. Adhesion force developed at real area of contact.



$$f = 1.07 * [\theta_I + \theta_{II}]^{2/3}$$

where E is young modulus, Mpsi

Where θ is

$$\theta = \frac{3.E + 4.G}{G(3.*E + G)}$$

where G is modulus in shear, Mpsi

Clean Steel E = 30 Mpsi, G=12 Mpsi

Aluminum E = 10 Mpsi, G=3.6 Mpsi

Titanium E = 15.5 Mpsi, G=6.5 Mpsi

Fig. : Examples on Tomlison formula.

- Fig. provides illustration related to Tomlison`s friction formula. This figure indicates f = 0.6558 for clean steel and aluminium, f = 0.742 for aluminium and titanium, and f = 0.5039 for clean steel and titanium.

Theories on Friction (Cont..)

❖ ***Scientific Explanation of Dry Friction :***

- There are two main friction sources: ***Adhesion and Deformation***. Force needed to plough asperities of harder surface through softer.
- In lubricated tribo-pair case, friction due to adhesion will be negligible, while for smoother surfaces under light load conditions deformation component of friction will be negligible.
- Fig. demonstrates the adhesion (cold weld) between two surfaces. Some force, F_a, is required to tear the cold junction.

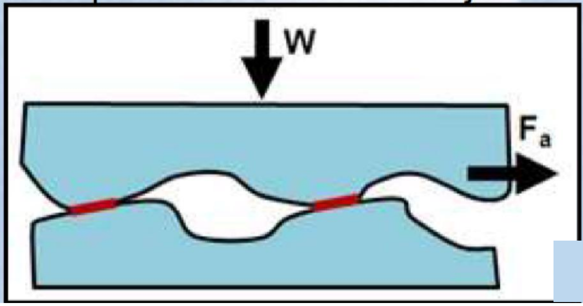


Fig. : Adhesion

[redacted]

Adhesion and Ploughing in Friction

- This theory is based on the fact that all surfaces are made of atoms.
- All atoms attract order one another by attractive force.
- For examples, if we press steel piece over indium piece (as shown in Fig.) they will bind across the region of contact.
- This process is sometimes called "cold welding," since the surfaces stick together strongly without the application of heat.

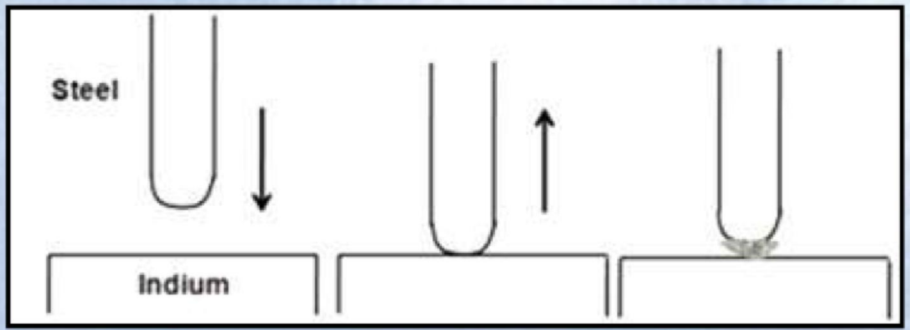
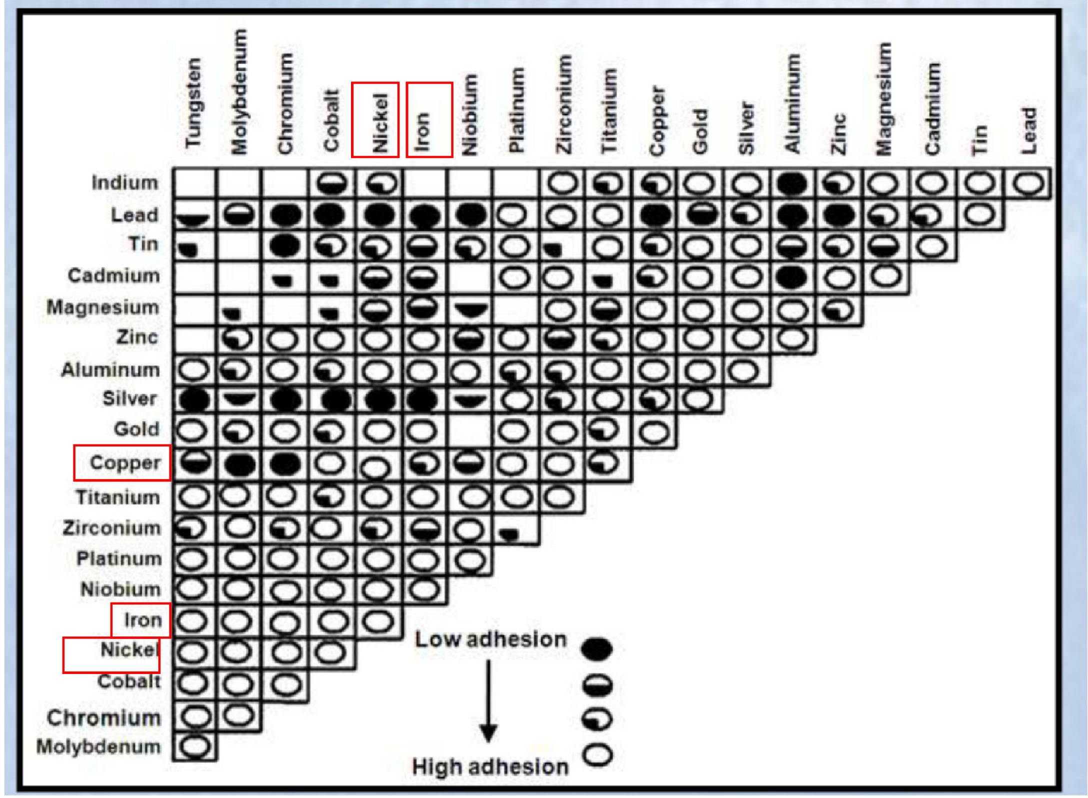


Fig. : Cold welding in steel and indium

Friction

INTRODUCTION…..(Cont..)

- Generally, adhesion (ref. Fig.) increases the friction. So, while selecting metal pairs, low adhesion metal pairs must be selected to reduce friction force. Similar material pair must be avoided as similar materials have higher tendency of adhesion.



THEORY OF ADHESIVE FRICTION (Cont..)

- Fig. shows the formulation and breakage of cold junctions. •
  - ✓ Two surfaces are pressed together under load W.
  - ✓ Material deforms until area of contact (A) is sufficient to support load W, A = W/H.
  - ✓ To move the surface sideway, it must overcome shear strength of junctions with force Fa.
  - ✓ μ = Fa/W = s/H.
  - ✓ In other words shear strength(s) and hardness(H) of soft material decides the value of μ.
  - ✓ This means whatever properties of the other harder pairing material, μ would not change.

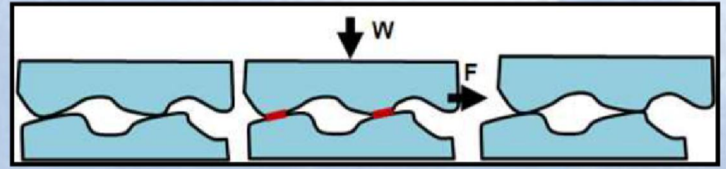


Fig. : Adhesion theory

FRICTION DUE TO DEFORMATION

- This theory is based on the fact that contact between tribo-pairs only occurs at discrete points, where the asperities on one surface touch the other.
- The slope of asperities governs the friction force.
- Sharp edges cause more friction compared to rounded edges.
- Expression for coefficient of friction can be derived based on the ploughing effect.
- Ploughing occurs when two bodies in contact have different hardness.
- The asperities on the harder surface may penetrate into the softer surface and produce grooves on it, if there is relative motion.

FRICTION DUE TO DEFORMATION (Cont..)

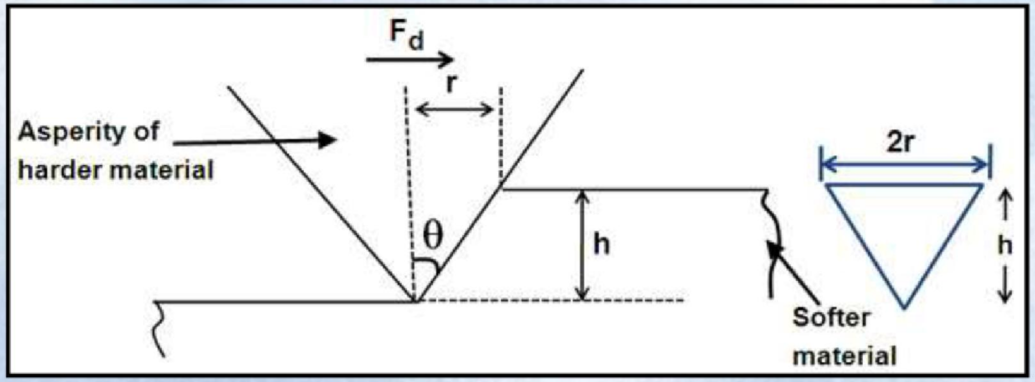


Fig. : Deformation theory[1].

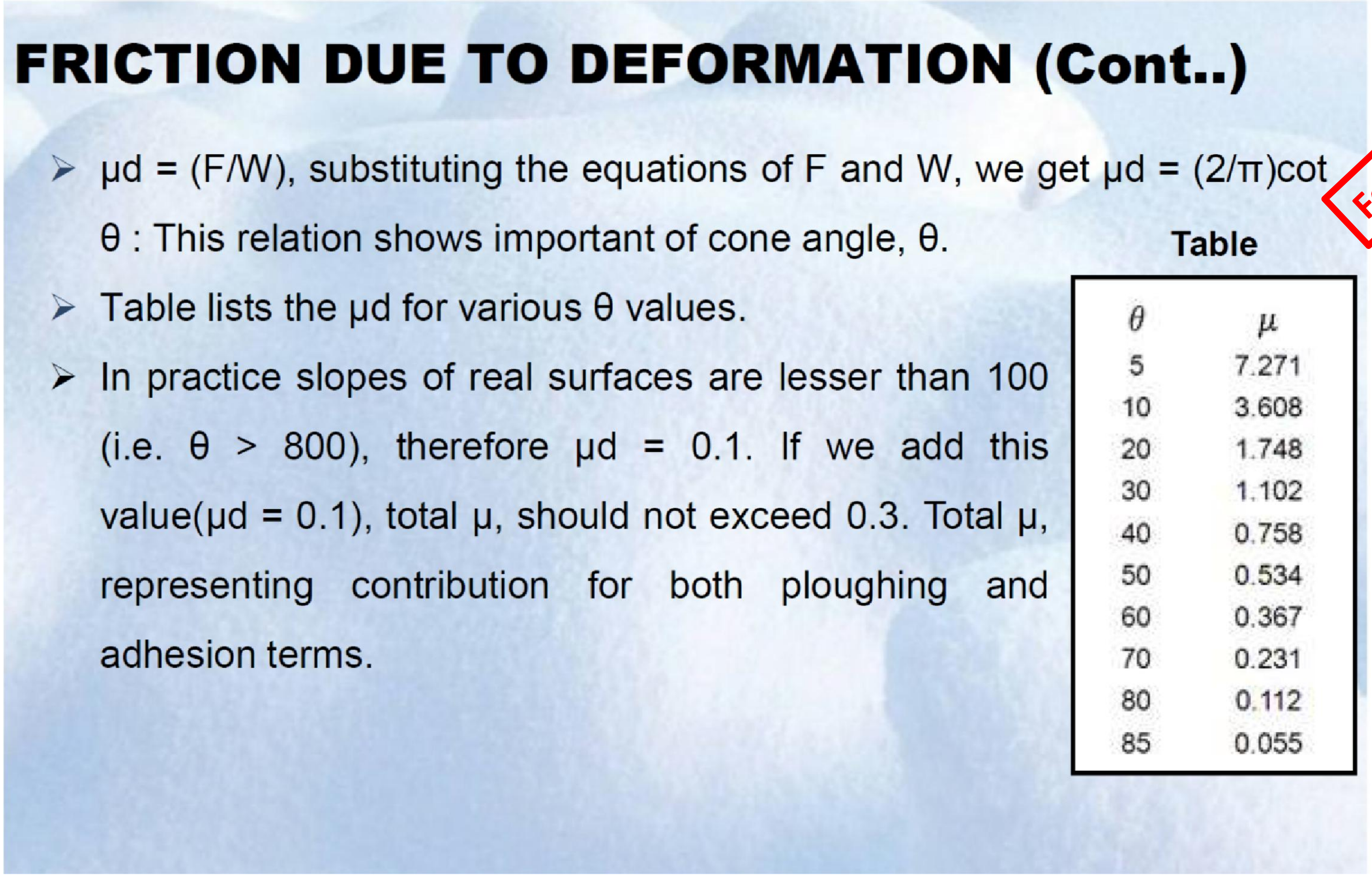
- Contact between tribo-pairs only occurs at discrete points. Assume n conical asperities of hard metal in contact with flat soft metal, vertically project area of contact.

$$W = n(0.5 * \pi r^2)H$$

$$A = n\left(0.5 * \pi r^2\right)$$

$$F = n(rh)H$$

[1]. J Halling, Principles of Tribology, The Macmillan Press Ltd, London, 1975.



FRICTION DUE TO DEFORMATION (Cont..)

- μd = (F/W), substituting the equations of F and W, we get μd = (2/π)cot θ : This relation shows important of cone angle, θ.
- Table lists the μd for various θ values.
- In practice slopes of real surfaces are lesser than 100 (i.e. θ > 800), therefore μd = 0.1. If we add this value(μd = 0.1), total μ, should not exceed 0.3. Total μ, representing contribution for both ploughing and adhesion terms.

Table

θ	μ
5	7.271
10	3.608
20	1.748
30	1.102
40	0.758
50	0.534
60	0.367
70	0.231
80	0.112
85	0.055

PLOUGHING BY SPHERICAL ASPERITY

- If we consider asperities on solid surfaces are spherical, vertical projected area of contact:

$$A = n\left(0.5 * \pi r^2\right)$$

$$or\ A = n\left(0.5 * \pi (0.5\ d)^2\right)$$

$$or\ A = n\ \frac{\pi d^2}{8}$$

$$W = n \frac{\pi d^2}{8} H$$

$$F = n\ \frac{2hd}{3} H$$

$$\mu_d = \frac{2hd8}{3\pi d^2} = \frac{16}{3\pi}\frac{h}{d} = \frac{16}{3\pi}\frac{h}{\sqrt{8hR}} = 0.6\sqrt{\frac{h}{R}}$$

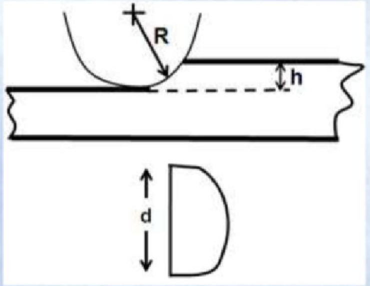


Fig. : Spherical asperity.

- Generally h << R, therefore μd Ξ 0.1. This means total μ, should not exceed 0.3. Summary of theories related to adhesion and ploughing effects.

PLOUGHING BY SPHERICAL ASPERITY (Cont..)

Adhesion, $\mu_a = \frac{s}{H}$

Deformation by Conical Asperities:

$$\mu_d = \frac{2}{\pi}\cot\theta = 0.64\frac{h}{r}$$

Deformation by Spherical Asperities:

$$\mu_d = 0.6\sqrt{\frac{h}{R}}$$

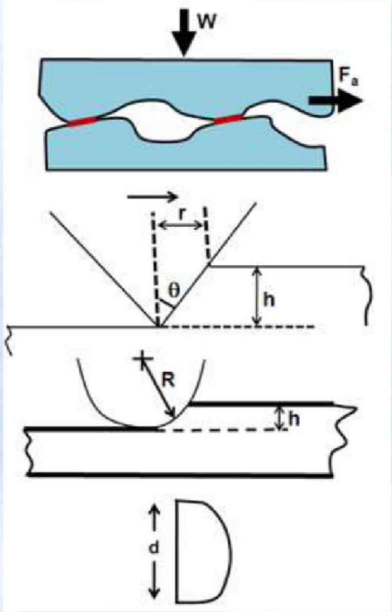


Fig.: Summary of adhesion and ploughing.

How do we measure friction?

Macroscale Friction Test

Friction tester under constant normal load
Geometrically constrained system

Microscale and Nanoscale Friction Test

Atomic force microscope (AFM)
Scanning probe microscope (SPM)
etc.

Friction at Nano- and Micro-scale Contacts

Macroscale

  >100 μm

  μ ~ 0.4 to 0.7

  Plastic deformation

- Microscale
  - ~ 10 μm
  - μ ~ 0.7 to 1
  - Surface energy, meniscus, and adhesion at the interface

- Nanoscale contacts
  - ~ 10 nm
  - Interatomic forces
  - μ ~ 0.07 (MD simulation results)

Measurement of Friction

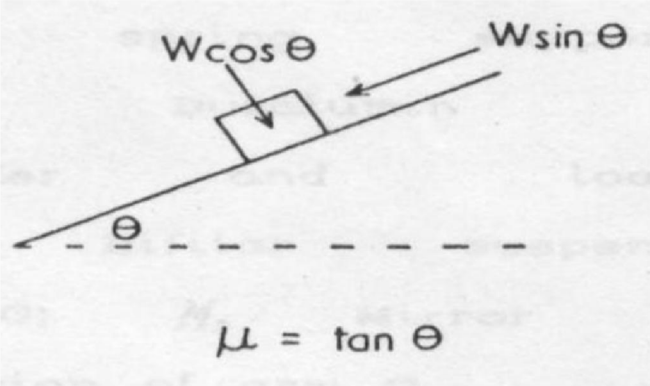
- To measure the friction, the basic requirements are simply a means of applying a normal load W and a means of measuring a tangential force F.

- Method -1:

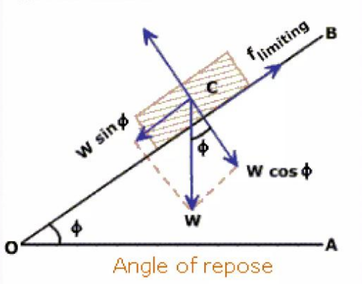
  If the lower surface is flat, the simplest method is to use the gravity loading and to tilt the lower surface until sliding begins

  If θ is the angle at which sliding begins, then, normal force = w cos θ, and tangential force = w sinθ,

  so that, μ = tan θ.

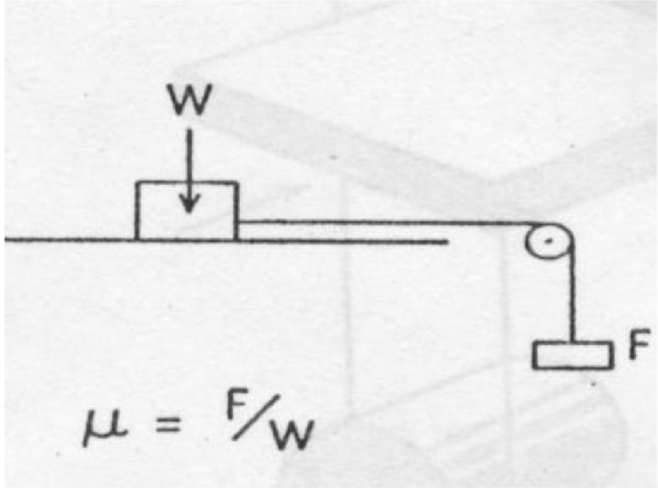


- With increase in angle of the inclined surface, the maximum angle at which body starts sliding down is called angle of friction.

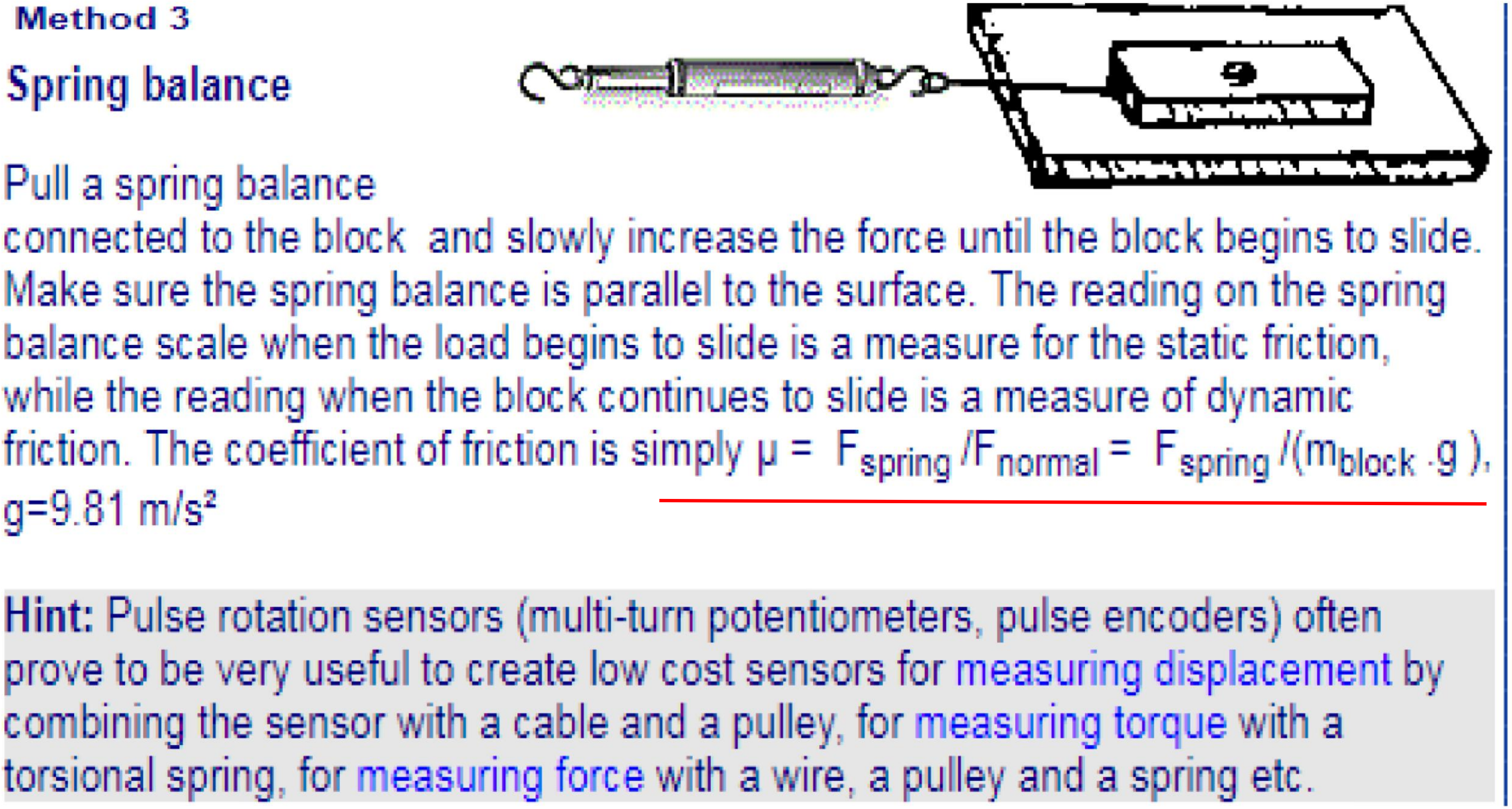


- It is a convenient quick rough method to determine μ, but the vibration during the tilting may produce error.
- Generally, once sliding is started at an angle θ, the upper body accelerates down the slope.
- This is because the friction to start sliding (the static coefficient of friction μs) is generally greater than the friction which arises during sliding (the coefficient of kinetic friction μk).

- The second method also uses the gravity loading but the lower surface is kept horizontal and the tangential loading is applied by means of dead load over pulley and μ = F/W.



- Both the methods are however, defective because of the inertia of the moving parts they cannot readily detect fluctuations which occur during sliding. For this reason, it is often more fruitful to use a device of high natural frequency. On the basis of this approach various sophisticated apparatus have been developed.



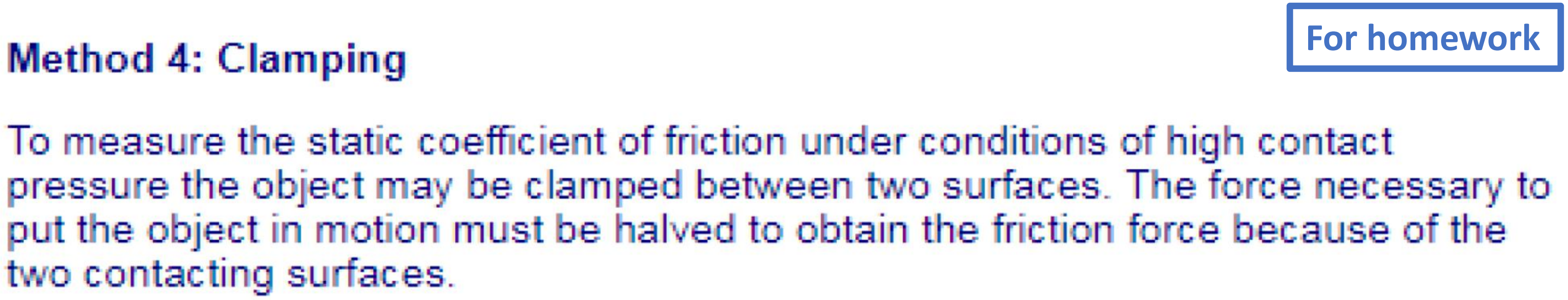
Method 3

Spring balance

Pull a spring balance connected to the block and slowly increase the force until the block begins to slide. Make sure the spring balance is parallel to the surface. The reading on the spring balance scale when the load begins to slide is a measure for the static friction, while the reading when the block continues to slide is a measure of dynamic friction. The coefficient of friction is simply $\mu = F_{spring} / F_{normal} = F_{spring} / (m_{block} \cdot g)$, $g = 9.81\ m/s^2$

Hint: Pulse rotation sensors (multi-turn potentiometers, pulse encoders) often prove to be very useful to create low cost sensors for measuring displacement by combining the sensor with a cable and a pulley, for measuring torque with a torsional spring, for measuring force with a wire, a pulley and a spring etc.

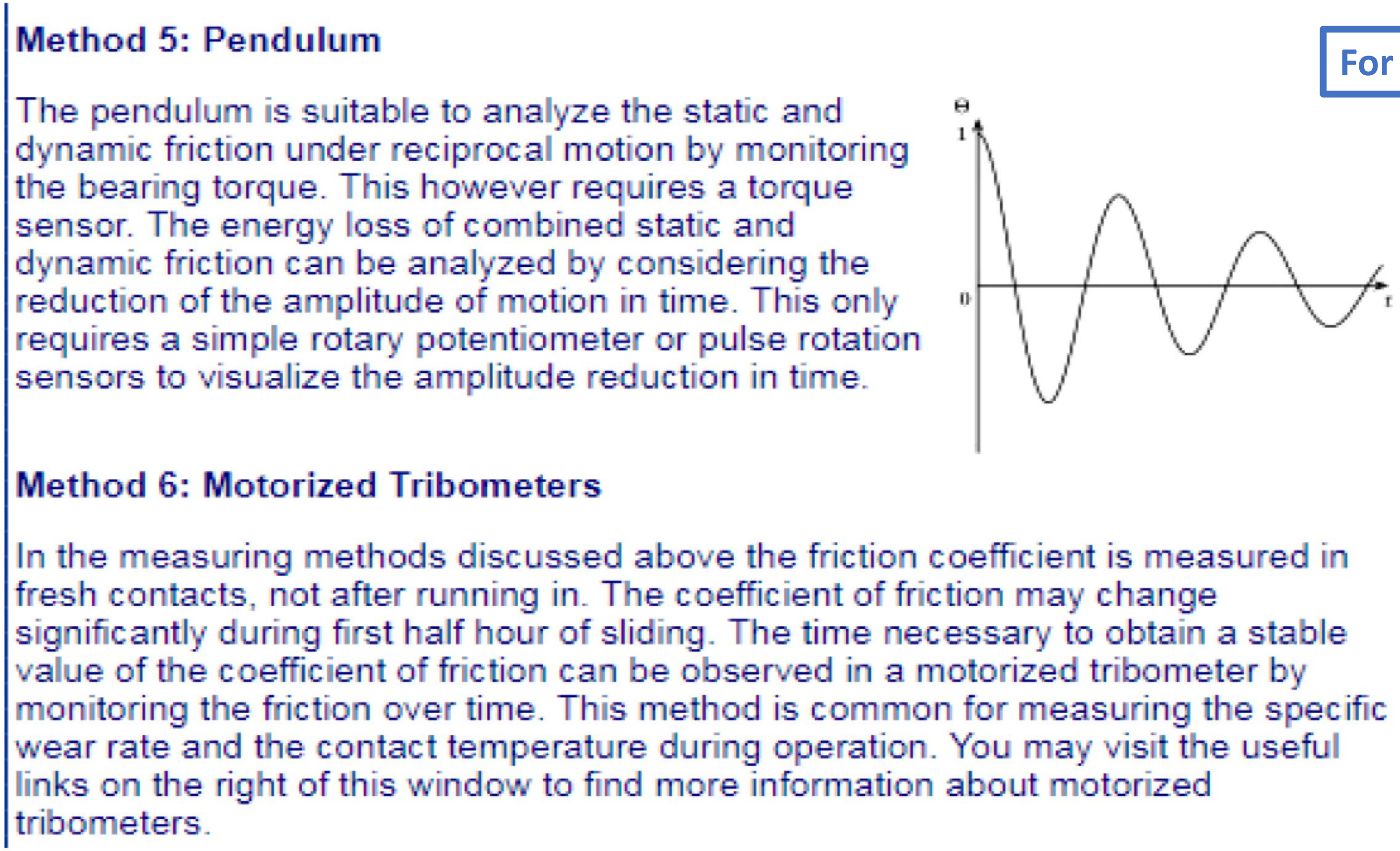
For homework



Method 4: Clamping

To measure the static coefficient of friction under conditions of high contact pressure the object may be clamped between two surfaces. The force necessary to put the object in motion must be halved to obtain the friction force because of the two contacting surfaces.

For homework



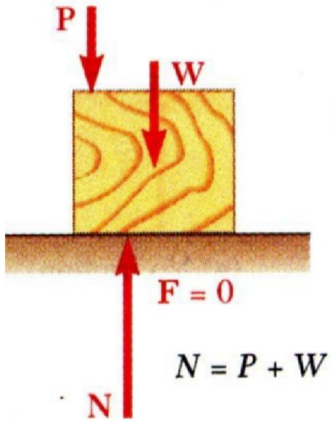
Method 5: Pendulum

The pendulum is suitable to analyze the static and dynamic friction under reciprocal motion by monitoring the bearing torque. This however requires a torque sensor. The energy loss of combined static and dynamic friction can be analyzed by considering the reduction of the amplitude of motion in time. This only requires a simple rotary potentiometer or pulse rotation sensors to visualize the amplitude reduction in time.

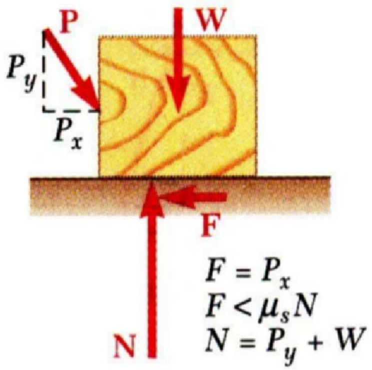
Method 6: Motorized Tribometers

In the measuring methods discussed above the friction coefficient is measured in fresh contacts, not after running in. The coefficient of friction may change significantly during first half hour of sliding. The time necessary to obtain a stable value of the coefficient of friction can be observed in a motorized tribometer by monitoring the friction over time. This method is common for measuring the specific wear rate and the contact temperature during operation. You may visit the useful links on the right of this window to find more information about motorized tribometers.

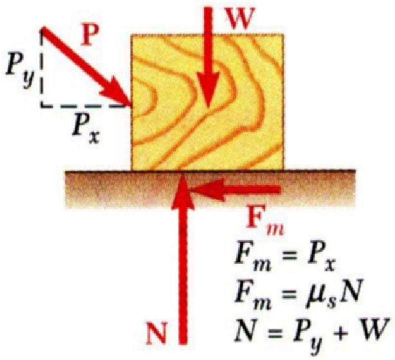
- Four situations can occur when a rigid body is in contact with a horizontal surface:



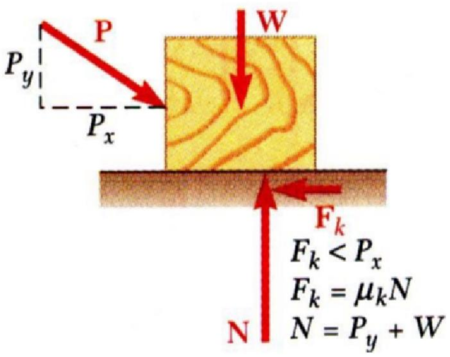
- No friction, $(P_x = 0)$



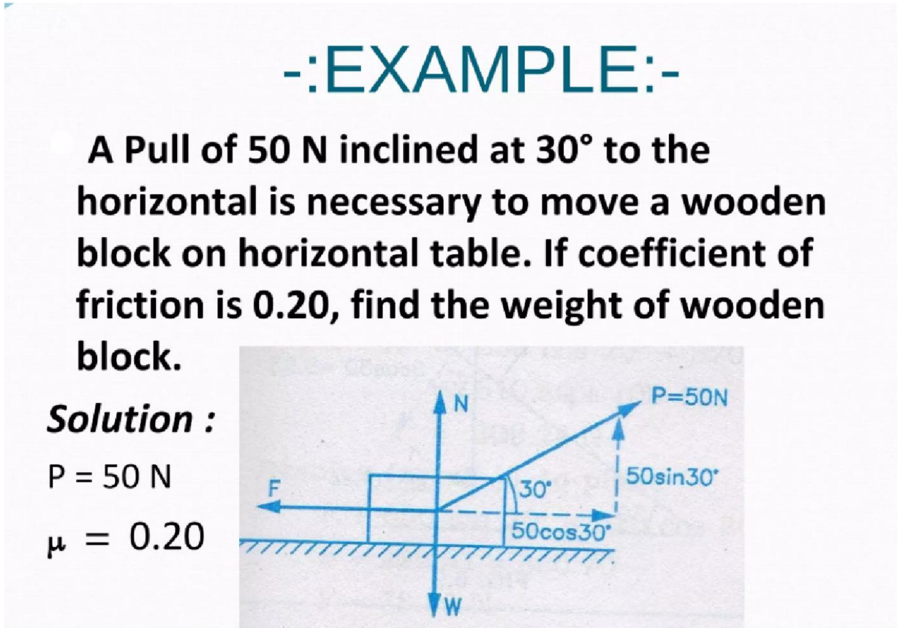
- No motion, $(P_x < F)$



- Motion impending, $(P_x = F_m)$



- Motion, $(P_x > F_m)$



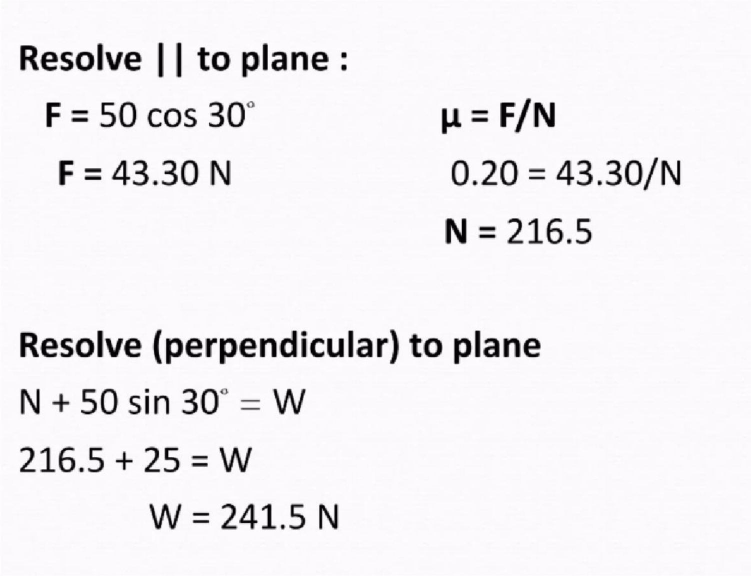
-:EXAMPLE:-

A Pull of 50 N inclined at 30° to the horizontal is necessary to move a wooden block on horizontal table. If coefficient of friction is 0.20, find the weight of wooden block.

Solution :

P = 50 N

$\mu = 0.20$



Resolve || to plane :

F = $50 \cos 30^{\circ}$

F = 43.30 N

μ = F/N

0.20 = 43.30/N

N = 216.5

Resolve (perpendicular) to plane

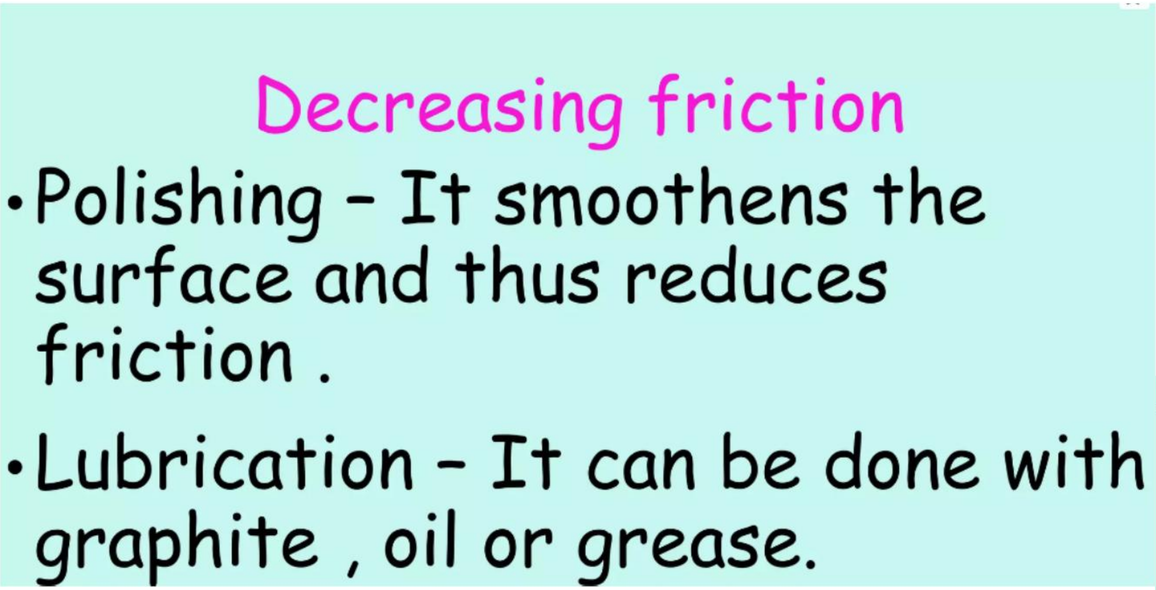
$N + 50 \sin 30^{\circ} = W$

216.5 + 25 = W

W = 241.5 N

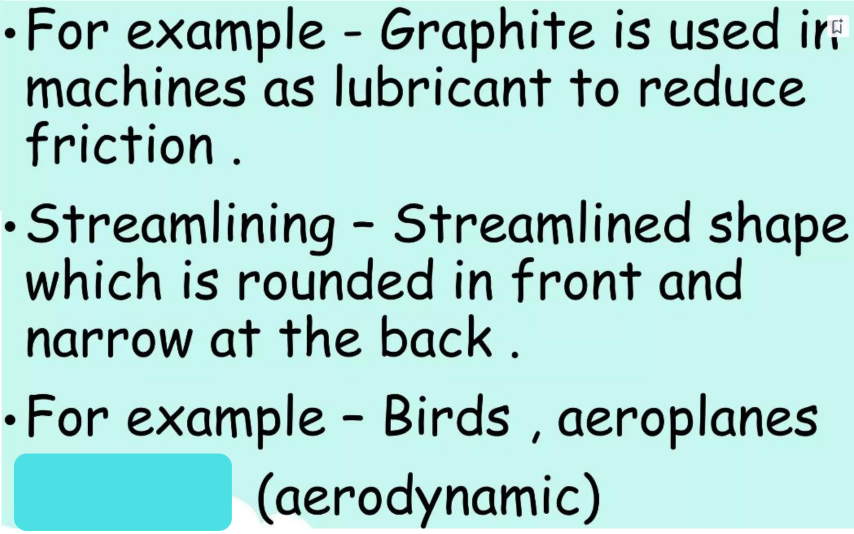
Friction is affected by the following:

1. Presence of wear particles and externally introduced particles at the sliding interface
2. Relative hardness of the materials in contact
3. Externally applied load and/or displacement
4. Environmental conditions such as temperature and lubricants
5. Surface topography
6. Microstructure or morphology of materials
7. Apparent contact area
8. Kinematics of the surfaces in contact (i.e., the direction and the magnitude of the relative motion between the surfaces



Decreasing friction

- Polishing – It smoothens the surface and thus reduces friction .
- Lubrication – It can be done with graphite , oil or grease.



- For example - Graphite is used in machines as lubricant to reduce friction .
- Streamlining – Streamlined shape which is rounded in front and narrow at the back .
- For example – Birds , aeroplanes (aerodynamic)

Streamlined shape of a car and a aeroplane .

polishing

Lubrication

Ball bearings

Wear